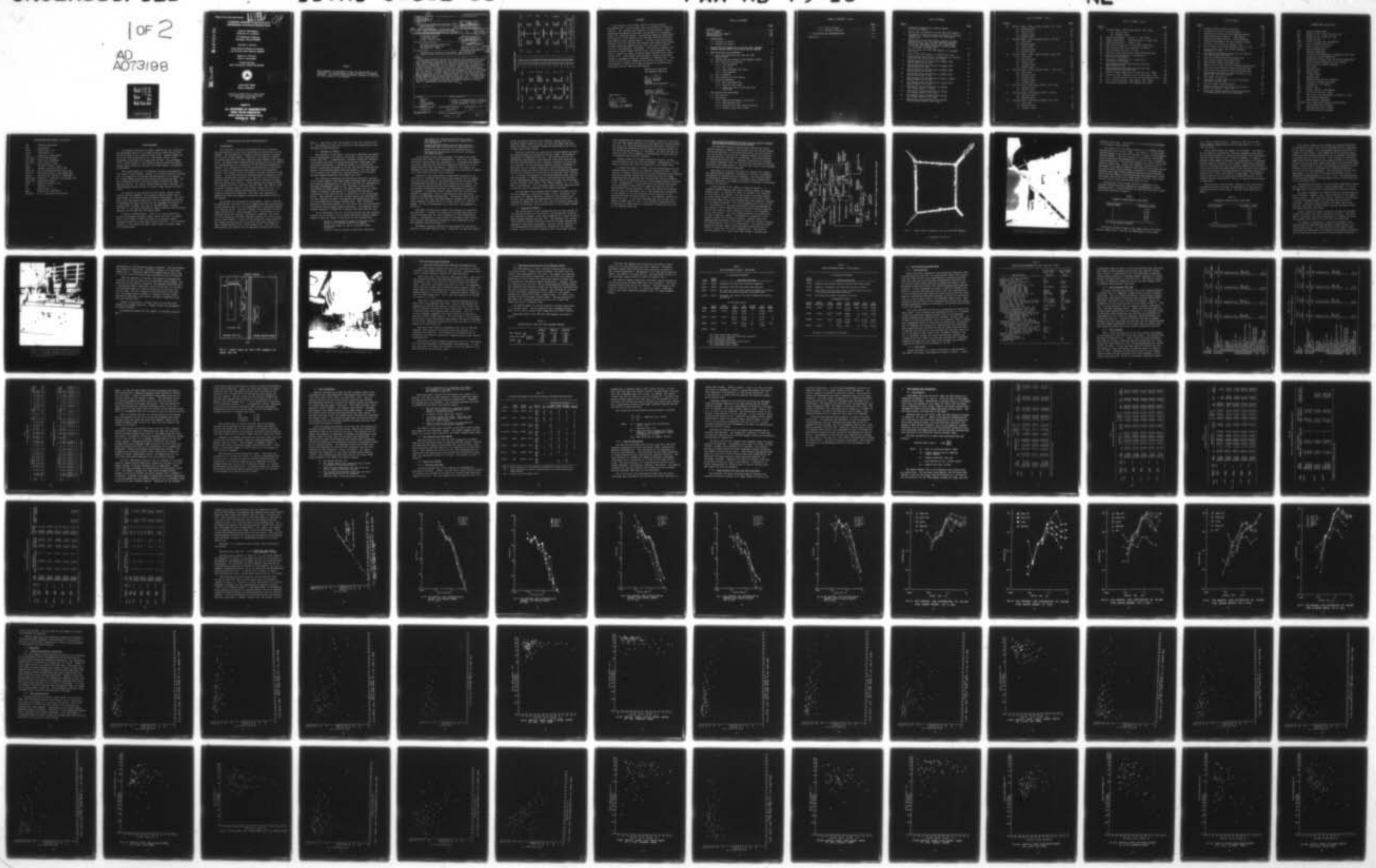
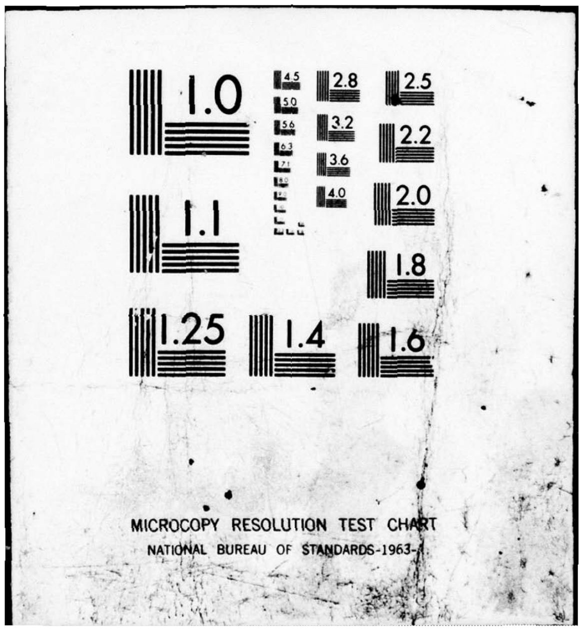
AD-A073 198 IIT RESEARCH INST CHICAGO IL F/G 21/5
TURBINE ENGINE PARTICULATE EMISSION CHARACTERIZATION.(U)
JAN 79 J D STOCKHAM, E H LUEBCKE, D L FENTON DOT-FA75-WA3722
UNCLASSIFIED IITRI-C6352-33 FAA-RD-79-15 NL

1 OF 2

AD
A073198




1.0
4.5
5.0
5.6
6.3
2.8
3.2
3.6
4.0
2.5
2.2
2.0
1.1
1.8
1.25
1.4
1.6
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

A073198

Report No. FAA-RD-79-15

LEVEL II

(12)

TURBINE ENGINE PARTICULATE EMISSION CHARACTERIZATION

A057370

John D. Stockham
Erdmann H. Luebcke

IIT Research Institute
Chicago, Illinois 60616

Donald L. Fenton

New Mexico State University
Las Cruces, New Mexico 88001

Ralph H. Johnson
Paul P. Campbell

United Airlines
San Francisco, California 94128

JANUARY 1979

FINAL REPORT

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL AVIATION ADMINISTRATION

Systems Research & Development Service

Washington, D.C. 20590

79 09 6 039

NOTICE

Technical Report Documentation Page

1. Report No. (18) FAA-RD-79-15 (19)	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle (6) TURBINE ENGINE PARTICULATE EMISSION CHARACTERIZATION,		5. Report Date (11) January 1979
		6. Performing Organization Code (14) IITRI-C6352-33
7. Author(s) (10) John D. Stockham, Erdmann H. Luebcke, Donald L. Fenton, Ralph H. Johnson, Paul B. Campbell		8. Performing Organization Report No. 33 (12) 130p.
9. Performing Organization Name and Address IIT Research Institute 10 West 35th Street Chicago, Illinois 60616		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. (15) DOT-FA75-WA3722
12. Sponsoring Agency Name and Address DOT-Federal Aviation Administration 800 Independence Avenue, S.W. Washington, D.C. 20591	A057370	13. Type of Report and Period Covered (9) Final Report. ~~6/10/78~~ - 12/31/79
		14. Sponsoring Agency Code 10 Jun 78 - 31 Dec 79

15. Supplementary Notes

The contract was conducted in three phases. Report FAA-RD-76-141 summarized Phase I and report FAA-RD-77-165 summarized Phase II.

16. Abstract

Particulate emissions from the TF-30, JT8D, and JT9D aircraft turbine engines were characterized for mass emission rate, particle size distribution, particle shape, and elemental composition as a function of engine type, fuel type, and power setting. Samples were collected from the exhaust plane of the engines with a sampling system developed under the contract. Two fuels were examined, Jet A and Pearl Kerosene. At idle power the TF-30 emitted 3.13 grams of particulate matter per kg of fuel consumed; the JT8D engine averaged 0.79 g/kg; no JT9D engine point was obtained. At takeoff power the TF-30 emitted 6.90 g/kg; the JT8D, 0.59 g/kg; and the JT9D, 0.38 g/kg. Geometric mean particle sizes ranged from 0.043 μm to 0.097 μm with particle size related to power level. Pearl Kerosene generally gave lower emissions and smaller particles than Jet A fuel. No elements were detected and it is assumed the particles are essentially carbon. Particle shape was difficult to quantify but the trend is for particle structure to be more complex or agglomerated at the higher power levels.

micron

17. Key Words Pollution Smoke Turbine Engines Aircraft Emissions Aerosols	18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	128	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

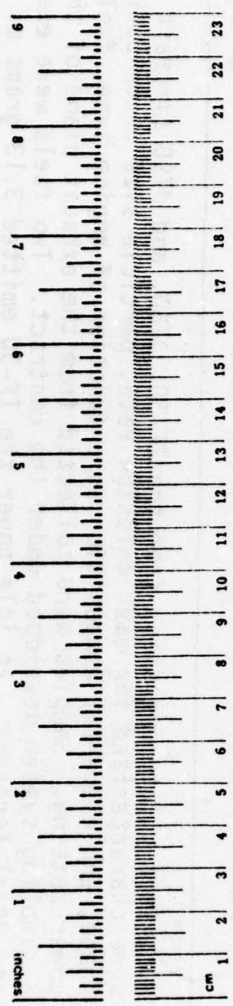
175350 VB

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

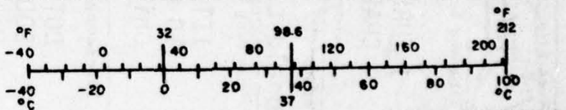
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

This document is the final report on Contract Number DOT-FA75WA-3722, "Turbine Engine Particulate Emission Characterization". The contract was conducted in three phases. Phase 1 determined the method of approach and resulted in a conceptual design of a sampling system. The sampling system was fabricated and tested on a TF30 engine at the National Aviation Facilities Experimental Center during Phase 2. In Phase 3 the particulate emissions from the JT8D and JT9D engines were sampled and characterized using the engines and test cell facilities at United Airlines, San Francisco, California. The results of Phase 1 are reported in Report Number FAA-RD-76-141, dated September 1976. Phase 2 results are given in Report Number FAA-RD-77-165, dated October 1977. Both reports are available through the National Technical Information Service, Springfield, Virginia 22161. The present report briefly summarizes the results of Phases 1 and 2 and presents in detail the characterization of the particulate emissions from the JT8D and JT9D engines.

Respectfully submitted,
IIT RESEARCH INSTITUTE

John D. Stockham
Science Advisor
Manager
Fine Particles Research

Erdmann H. Luebcke
Assistant Engineer
Fine Particles Research

Approved by,

Irvine J. Solomon
Director
Chemistry and Chemical
Engineering Research

TABLE OF CONTENTS

TABLE OF CONTENTS (cont.)

LIST OF FIGURES

LIST OF FIGURES (cont.)

LIST OF FIGURES (cont.)

LIST OF TABLES

NOMENCLATURE AND SYMBOLS

EPR	Engine Pressure Ratio
W_{at}	Weight of air, total, fan plus core
W_{ap}	Weight of air, primary or core
W_f	Weight of fuel
TSFC	Thrust Specific Fuel Comsumption
F/A_p	Fuel to primary air ratio
F/A_T	Fuel to total air ratio
PK	Pearl Kerosene fuel
T_1	Ambient temperature
T_4	Diffuser case temperature, combustion zone inlet
T_5	Combustion outlet temperature
T_6	Temperature between first and second compressors
T_7	Turbine outlet temperature, last turbine
P_{s_4}	Static pressure before combustor
I	Idle power
App	Approach power
Cru	Cruise power
CO	Climbout power
TO	Takeoff power
d_g	Geometric mean particle diameter
σ_g	Geometric standard deviation
µm	Micrometers, 10^{-6} meters
lbm	Pounds, mass
lbf	Pounds, thrust, 4.448 newtons
TSO	Time Since Overhaul, hours
HM	Time since Heavy Maintenance inspection, hours
N_1C	Low pressure compressor
N_2C	High pressure compressor
1st NGV	First stage high pressure turbine nozzle
N_1T	Low pressure drive turbine
N_2T	High pressure drive turbine
EAA	Electrical Aerosol Analyzer

NOMENCLATURE AND SYMBOLS (continued)

EM	Electron microscopy
API	API gravity
FzPt	Freeze Point, ^{o}F
FlaPt	Flash Point, ^{o}F
Visc	Viscosity, centistrokes
Anil Grav	ASTM D 1655 gravity
Tot Acid	Total Acid, mg KOH/g
Tot sulf	Total Sulfur, % wgt
Merc	Mercaptan sulfur, % wgt
Coker	Thermal stability ASTM D 1660
Coker PR	Filter maximum pressure drop, "Hg
Coker TU	Pre-heater deposit, non-dimensional
Gum Ex	Existent gum, mg/100 ml, ASTM D381
Water App	Appearance, interface rating ASTM 1094
Water Sep	Separation rating
Arom	Aromatic content, % vol.
Oil	Olefins, % vol.
Na	Naphthalene, % vol.
SmPt	Smoke Point, ASTM D1322
Hydrogen	% vol. calculated and measured

ACKNOWLEDGEMENT

IIT Research Institute is deeply indebted for the cooperation and assistance given by the Federal Aviation Administration and United Airlines in the conduct of this study. Special thanks are due to Mr. William Westfield, Mr. John Tigue, and Mr. Larry Taubenkibel who guided the program for the FAA. The assistance of Mr. Gerald Slusher at the National Aviation Facilities Experimental Center during the testing on the TF30 engine is gratefully acknowledged.

Many staff members at IIT Research Institute contributed to the success of the program. Messrs. E. W. Nordstrom and W. Courtney were instrumental in the design and fabrication of the sampler. Mr. George Yamate performed the electron microscopy and Mmes. Jean Graf, Katherine Severin, and Carla Plemich provided the image analyzer results. Mr. Martin Murray aided in data reduction. Dr. Prem Bhardwaja served briefly as project leader during the Phase 3 effort.

In addition to the coauthors of this report, Messrs. Ralph Johnson and Paul Campbell, IIT Research Institute would like to acknowledge the following United Airlines staff members: Mr. Arne Wahl, staff maintenance specialist, for his invaluable assistance in modifying the test cells for the test equipment and Messrs. E. George Finato, Foreman, Test Cell 5, and Bob Updall, Foreman, Test Cell 3, for their assistance in engine selection and providing manpower for the JT8D and JT9D engine tests.

A special acknowledgement is due to Dr. Donald Fenton who served the program as project leader during the first two phases while on the staff of IITRI and later as a consultant after accepting a position at New Mexico State University. His continued interest in the program provided a much needed continuity among the program phases.

TURBINE ENGINE EMISSION CHARACTERIZATION

1. INTRODUCTION

The objective of Contract DOT-FA75WA-3722 was to measure and characterize the particulate emissions of aircraft gas turbine engines. The information is needed to develop emission standards for aircraft turbine engines. Presently, the emission standard for particulate matter is based upon the smoke number of the exhaust plume. The smoke number measures plume opacity and does not address the characteristics or concentration of the particles themselves. However, it is necessary to know the characteristics of the particles in order to understand their formation in the combustion process, their impact on the environment, and their possible health effects. The particulate matter characterization conducted on this contract included mass emission rate, particle size distribution, particle shape, and elemental composition as a function of engine type and engine power setting. Three engines were examined during the program, the TF-30, the JT8D, and the JT9D. The JT8D and JT9D represent turbofan engines in the current commercial fleet. The TF-30 is a military engine representative of the era prior to smokeless combustion technology. All tests were conducted in engine test cells with samples collected at the exhaust plane of the engines.

The program was conducted in three phases. Phase 1 entailed a comprehensive literature review of sampling methods and emissions characterization and led to the development of a conceptual design of a sampling system. Results of Phase 1 were reported in Report Number FAA-RD-76-141, dated September 1976. During Phase 2 the sampling system was designed, fabricated, assembled, and tested on a TF-30 engine at the FAA's National Aviation Facilities Experimental Center (NAFEC). Details of the design and construction of the sampler and the results of the TF-30 tests were reported in Report Number FAA-RD-77-165, dated October 1977. The JT8D and JT9D engines were sampled and the emissions characterized during

Phase 3. The results from this series of tests are reported herein. The engines and test cell facilities used during Phase 3 were furnished by United Airlines.

1.1 Synopsis of Phase 1

The objective of the Phase 1 study was to determine the method for the measurement and analysis of aircraft turbine engine particulate emissions. A comprehensive literature review was conducted to determine the status of particulate analysis technology; and, using this information, a conceptual design of a sampling and analysis system was developed to collect and analyze representative samples of particulate matter from the exhaust at the exit plane of low bypass ratio, mixed flow, and high bypass ratio aircraft turbofan engines operating in an engine test cell.

The literature concerning the particulate emissions from aircraft turbine engines indicated present knowledge about the physical and chemical characteristics of the particles was not comprehensive. Aerospace Recommended Practice 1179[1] describes a procedure for determining the smoke number of the exhaust plume; but, the smoke number is related to the opacity of the plume and provides no information on the particle size or composition of the particulate matter. Mass emission rates for various engines were measured[2,3,4,5] but only Johanson and Kumm[4] investigated the experimental difficulties concerned with obtaining reliable data. Sem[6] informally reported a count mean diameter of 0.023 μm for the size distribution of aircraft turbine engine exhaust particles. The extensive microscopical analysis of Broderick[7] supported this mean particle size.

It was determined from the literature review that the essential features of an aircraft turbine engine particulate exhaust sampler needed to meet the technical objectives of this program were:

- Extract a representative sample of the particulate matter at the exhaust plane of the engine.
- Collect the sample as soon as practical after extraction.
- Provide a sample transport system that conditions

the sample for collection and minimizes sample alteration due to wall deposition, agglomeration, and condensation.

- Acquire separate samples for the mass emission measurement and for the particle characterization.
- Measure the mass emission rate gravimetrically.
- Characterize the particles by electron microscopy and image analysis.

In the design of the sampling probe, the engine exit plane velocities were noted to not exceed Mach 1. With this, the sample extraction nozzle design was approached in a straightforward manner. Isokinetic sampling was found to be marginally important for the larger particle sizes anticipated. Therefore, the sampler was designed for flow adjustment to accommodate the variations in engine exit plane velocities with power settings.

Analysis of the mixing probe configuration resulted in the selection of a modified FAA emission rake geometry for the sampler. The selection was based on the performance of other mixing probe configurations and gaseous emissions concentration profiles. Use of the gaseous emission profiles was mandated by the absence of particulate concentration profiles for the engines of interest to the program. A technical report[8] issued after this decision was reached is supportive. Here, a FAA emissions rake was tested against the NASA/P&WA emissions rake. The results showed that the levels of CO, THC, NO_x, and smoke numbers obtained with these two rakes compared to within 10% at all power levels for a JT9D-20 engine. If the CO measurements are eliminated, the agreement is within 5%.

The sample conditioning assembly was designed to accomplish two functions: transport the sample with minimum deposition and dilute the sample for dew point, temperature, and concentration control. Fortunately, a ready design of a boundary layer diluter was available from previous research at IITRI sponsored by the Environmental Protection Agency.[9,10]

Gravimetric analysis offered the best method for the determination of the mass emission rate. Trade-offs of important sampler

design parameters such as filter diameter, sample flow rate, available engine operation time, and size and weight were made before arriving at an optimal design and selection of the 142 mm diameter glass fiber filter.

Electron microscopy was selected as the only method available for characterizing the parameters of size, shape, and elemental composition of submicron particles. The filters used for the gravimetric measurement of mass emission rates were unsuited for particle characterization and a separate collection of particles was required. Of the collection methods surveyed, diffusion of particles from the sample stream onto carbon-coated electron microscope grids and direct filtration onto polycarbonate membrane filters were selected as convenient to execute with high reliability. To assist the operator in selecting sampling times, the real time measurement of number particle concentration was desirable. Of the instrumental methods commercially available the Electrical Aerosol Analyzer, EAA, (Model 3100, Thermo Systems, Inc., St. Paul, Minn.) was selected. This instrument would provide supportive data on particle size distribution of the exhaust particles.

The remainder of the design work included the specifications of flow parameters, selection of pumps, valves, and meters, and provisions for remote operation, acoustical and vibration protection, and cleansing the compressed air used for dilution. The constraints imposed by the test cell, such as internal dimensions, location of utilities, also provided input to the ultimate design.

1.2 Synopsis of Phase 2

The second phase of the program involved the final design of the sampling system, its construction, and preliminary check-out and operation at NAFEC. Tests were conducted on a single TF-30-P-1 engine during February and June 1977. The February tests identified sampling problems which were corrected through redesign and changes in operational procedures. The test series conducted in June demonstrated the repeatability inherent in the sampling system. Using the TF-30-P-1 engine at the cruise power setting,

four consecutive mass emission measurements agreed to within ±2%; with the same engine operated at cruise power on the three different days, the variation experienced was about ±9%. Precision of the parameters associated with the physical characterization of the particles was difficult to determine. The data from the consecutive cruise tests suggests a repeatability of about ±7% for the geometric mean particle diameter.

Despite efforts to provide acoustical barriers, the EAA malfunctioned in the test cell environment. Subsequently, it was removed from the test cell and operated in the control room.

A significant aspect of Phase 2 was the determination of the optimum method of analysis for particle characterization. Examination of "marker" electron grids by both transmission and scanning electron microscopy showed that the particles did not change morphology with storage and that the particles did not preferentially collect on the grid wires as some charged aerosols are prone to do. Subsequently, it was noted that the electron microscope grids exhibited a lower particle deposition density than the polycarbonate filter substrate to which the grids were attached. The bias was not quantified; but it was decided that observation of the deposit on the polycarbonate filter substrate by SEM provided the most reliable results at a considerable reduction in analytical time. It was also concluded that the diameter of a sphere of area equal to that of the irregular shaped particles, as measured by image analysis, would best characterize the size of the emission particles.

2. DESCRIPTION AND OPERATION OF THE FAA-IITRI AIRCRAFT TURBINE ENGINE EXHAUST PARTICULATE MATTER SAMPLER

The FAA-IITRI aircraft turbine engine particulate matter sampler acquires a sample of the exhaust particles emitted during the ground operation of the engine and permits the characterization of the mass concentration, elemental composition, particle size distribution, and particle morphology. Mass concentration is obtained gravimetrically. Elemental composition is obtained by energy dispersive X-ray and particle size and shape by electron microscopy and image analysis. Particle size data is also obtained with the Electrical Aerosol Analyzer.

The sample is extracted from the exit plane of the engine. The sampling probe geometry corresponds to the FAA's recommended methodology for gaseous emission sampling. The extracted sample is conditioned through dilution to minimize local condensation, particle deposition, and sample bias before collection on substrates suitable for analysis.

A flow diagram of the sampler is shown in Figure 1. A "diamond" shaped sampling rake mounts directly behind the engine exhaust plane. An extraction nozzle is located at the midpoint of each leg of the diamond. The four nozzles are evenly spaced on an arc whose radius is 62% of the engine's exit plane radius. The leading edge of the nozzle extends about ten diameters upstream of the support structure. The nozzle diameters are 0.170 ± 0.008 cm. The geometry of the rake corresponds to that recommended by the Federal Aviation Administration for gaseous emission sampling and has been shown to give comparable results to a 24 sampling nozzle rake system.[8] The four sampling nozzles are manifolded to provide a composite sample. The manifold is connected to the primary diluter via a flexible coupling. Figure 2 shows the sampling rake and manifold and Figure 3 shows the flexible coupling and primary diluter with its tripod support. The tripod provides adequate elevation, angular and rotational translation for the diluter to meet most test cell configurations. The flexible coupling consists of a steel foil liner inside a bellows-type,

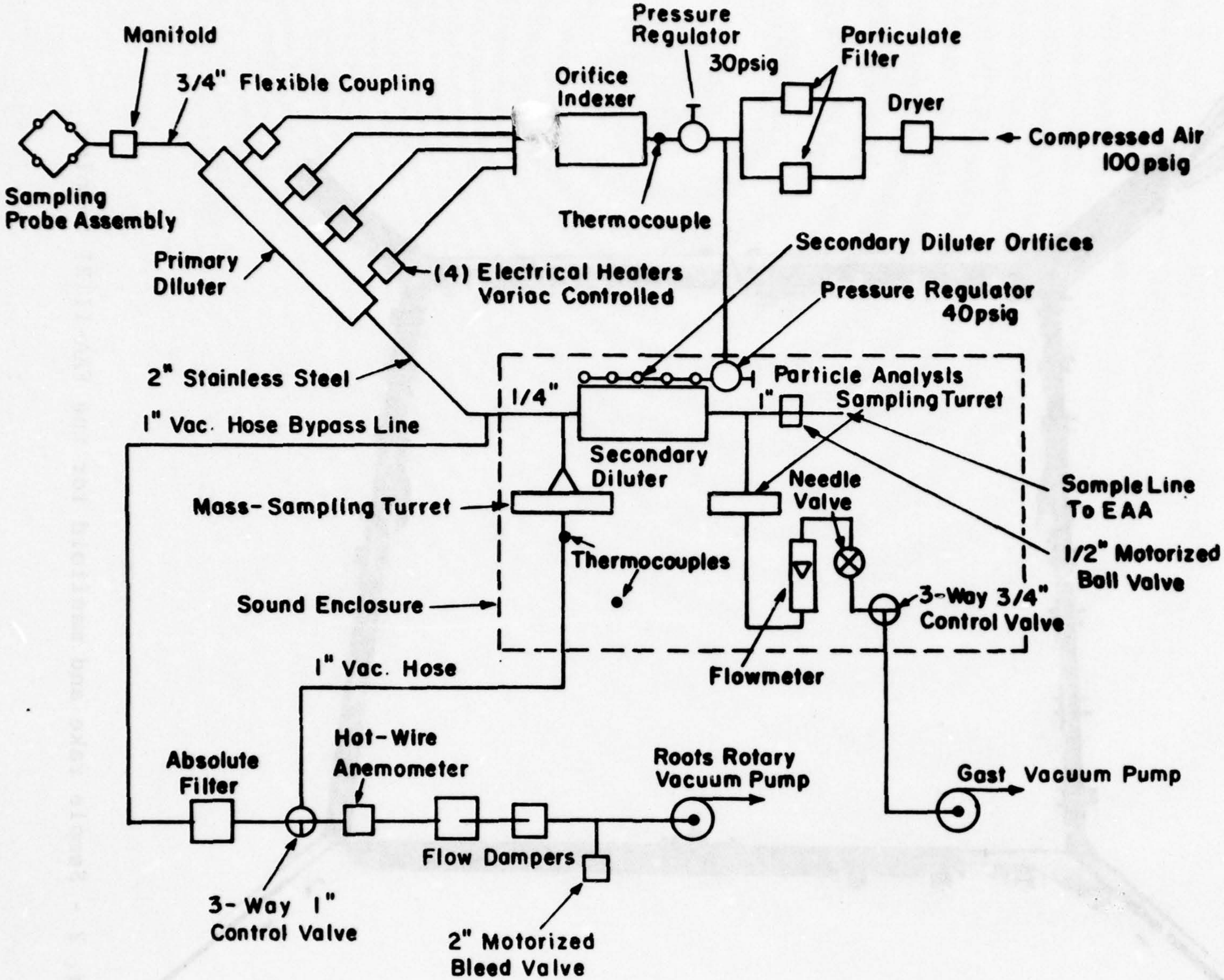


Fig. 1 - Schematic diagram of the engine exhaust particulate sampler

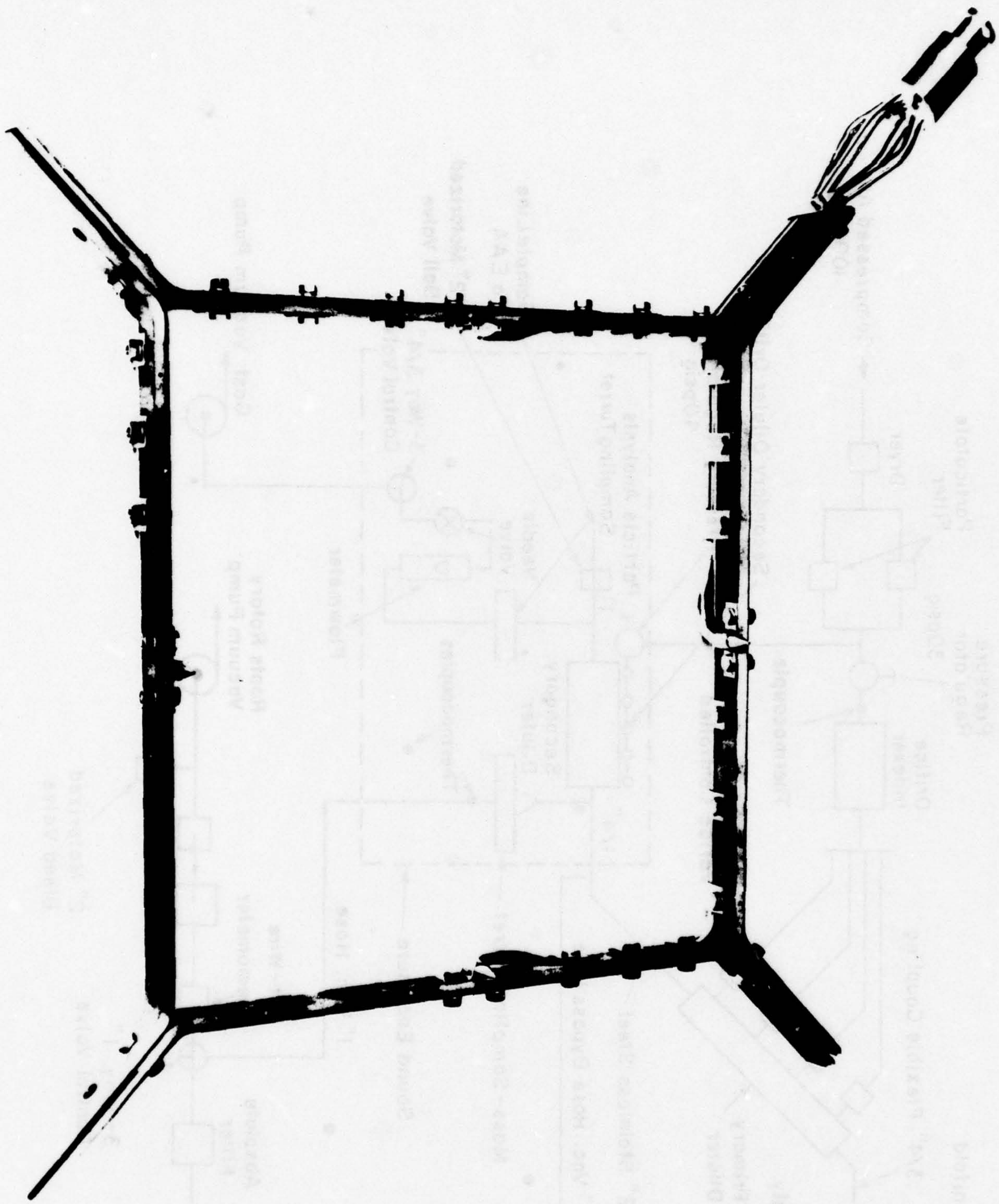


Fig. 2 - Sample rake and manifold for the FAA-IITRI Sampler.

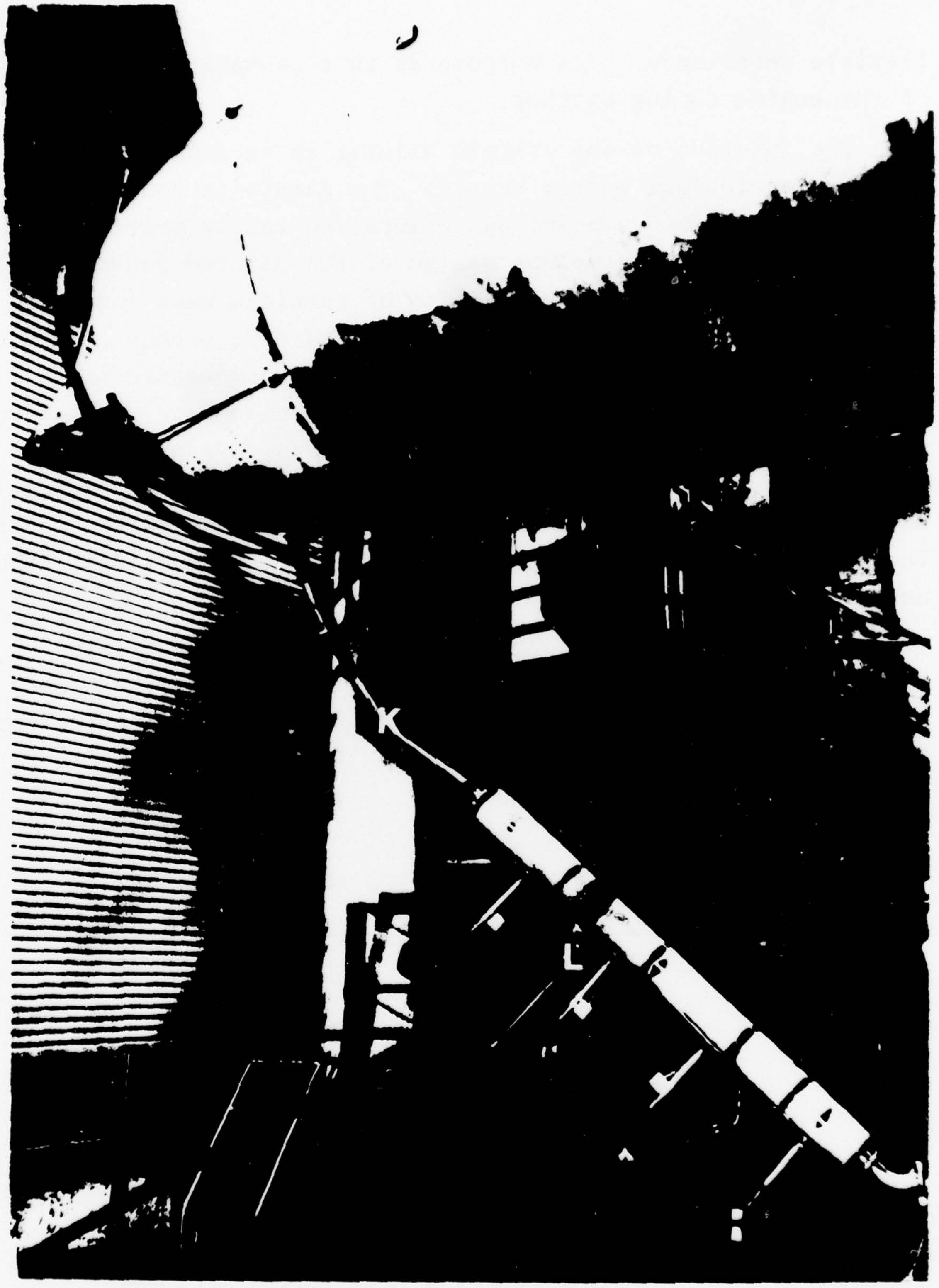


Fig. 3 - Photograph of FAA-IITRI Sampler showing the flexible coupling (K), Primary Diluter (E), and Tripod Support (L).

flexible metal hose. Its purpose is to accommodate the movement of the engine during testing.

The function of the primary diluter is to condition the extracted particulate matter sample. The sample is cooled without passing through a dew point and diluted to reduce particle agglomeration effects. The unique design of the diluter reduces wall losses and aids in the preservation of particle mass and particle size distribution.[9,10] The diluter consists of a porous tube housed within a larger tube. Clean, dry, metered, compressed air is delivered to the annular space at four locations and flows through the porous inner tube providing a continuously displaced clean boundary layer that reduces particle deposition and subsequently mixes with the sample to provide dilution and temperature control. The porous tube is 183 cm in length with a 5 cm ID, a wall thickness of 0.16 cm, and a nominal pore size of 2 μm.

Dilution air to the primary diluter is metered by five precision drilled orifices mounted in a pneumatically powered indexable plate. Orifice selection is made from the control panel. Flow rates are given in Table 1.

Table 1

PRIMARY DILUTER ORIFICE FLOW RATES

Orifice Number	Flow Rate, m^3/hr^*
1	4.32
2	10.08
3	15.30
4	18.90
5	31.14

*at 30 psig supply pressure

Calculated residence times of the sample within the primary diluter ranged from 7.3 sec for the JT8D engine at idle power

to 4.5 sec at take-off power. Residence times for the JT9D engine samples ranged from 9.0 sec at idle power to 4.9 sec at take-off power.

After conditioning, the sample is bifurcated. The majority of the sample is transported to the mass sampling turret where the particulate matter is removed by filtration onto tared Gelman, type AE, glass fiber filters, 142 mm in diameter. A smaller portion of the sample is adjusted in concentration by a secondary diluter similar in design to the primary diluter and transported either to the Electrical Aerosol Analyzer (EAA) for real-time particle size distribution measurement or for collection onto membrane filters and electron microscope grids for subsequent analysis of particle size, shape, and elemental composition. The membrane filters used are 0.03 μm pore size Nuclepore(R) filters, 47 mm diameter backed by Millipore(R) filters to improve the uniformity of deposition.

The air flow to the secondary diluted is also controlled by 5 precision drilled orifices, any combination of which can be selected from the control panel. The flow rates are given in Table 2.

Table 2

SECONDARY DILUTER ORIFICE FLOW RATES

Orifice Number	Flow Rate, m^3/hr^*
1	0.34
2	0.45
3	0.27
4	0.29
5	0.97
Total	2.32

* at 40 psig supply pressure

Flow control valves for the sampler are located downstream of the particle collection sites to eliminate particle deposition in the valve assembly. This requirement imposed operational constraints in the system -- each sample has to be acquired sequentially and flow switching procedures must be carefully performed to prevent rupture of the filters. Also, because the extracted sample flow from the engine is not measured directly, the primary diluter flow and the total sample flow have to be accurately determined. The dilution flow rates are measured by precision drilled orifices; total flow is measured with a 1000-2B Datametrics, 0-108 m^3/hr, hot-wire anemometer. The uncertainty in total flow measurement is $\pm$ 0.09 std. m^3/hr while the dilution flow is repeatable to approximately $\pm$ 0.1 std. m^3/hr. The maximum error in the extracted sample flow measurement occurs at idle power and is on the order of 10%.

The principle air mover is an AF-33 Roots-Connersville blower with a range of 9 to 72 m^3/hr. A Gast vacuum pump, 7.2 m^3/hr @ 659 mmHg serves the particle characterization collection system.

The turret assemblies for sample collection provide positions for six filters. Samples, thus, can be acquired at five engine power settings -- idle, approach, cruise, climb-out, and take-off -- before the engine needs to be shut down and the filters recovered. The sixth turret position is a dummy used during start-up, shut-down, and while power settings are being changed and engine operation stabilized.

Figure 4 shows the sample collection turrets and secondary diluter set within the sound attenuation enclosure. The Roots Blower, flow meter, and house compressed air cleaning and metering equipment are mounted on top of the sound attenuator.

The sampler is designed for isokinetic sampling of the exhaust from the JT8D and JT9D engines at power settings from idle through cruise. At climb-out and take-off power, sonic conditions are approached at the engine's exit plane and sampling at this rate would cause severe flow complications resulting in

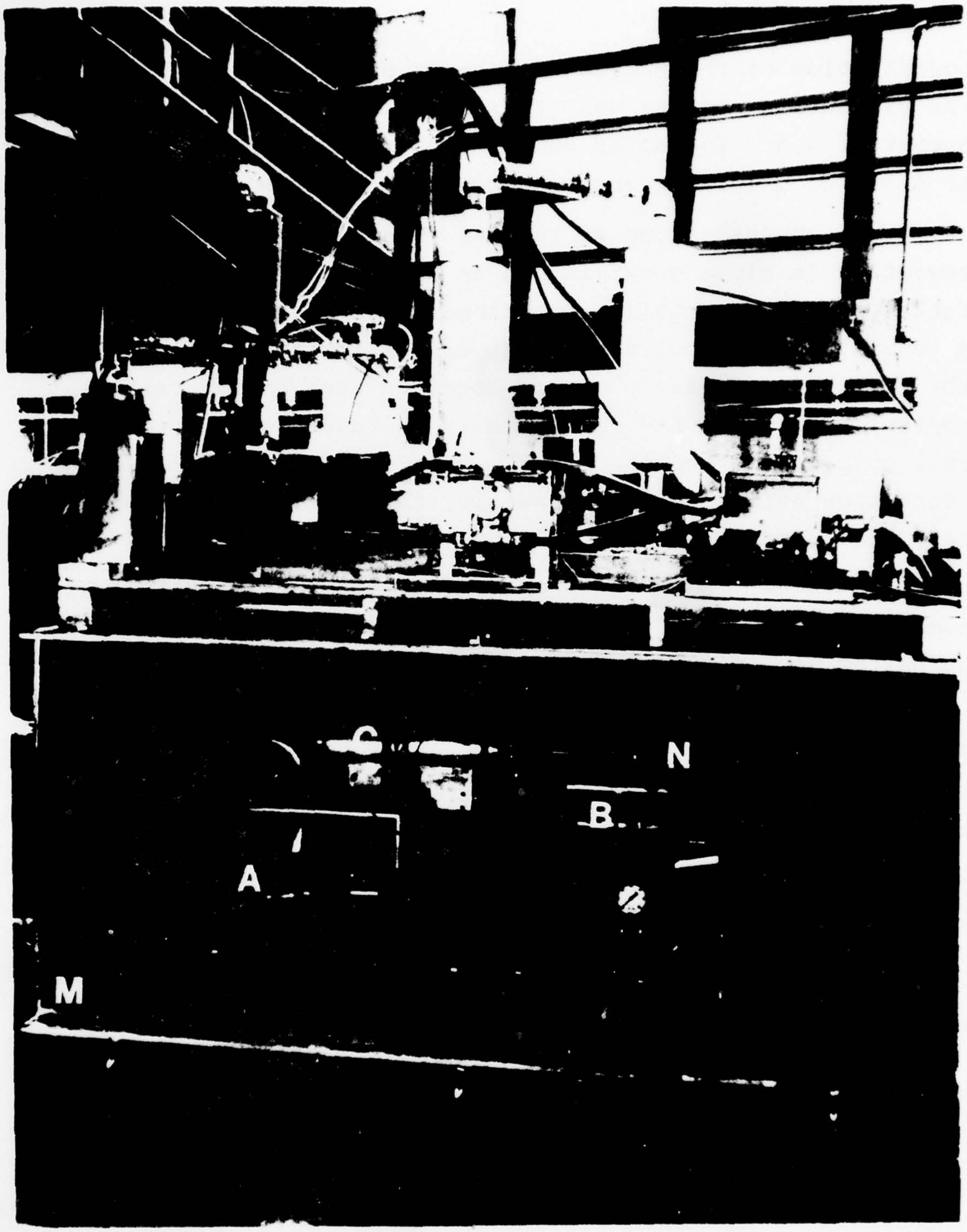


Fig. 4 - Photograph of FAA-IITRI Sampler showing the Mass Sampling Turret (A), Particle Analysis Sampling Turret (B), Secondary Diluter (C), Sample line to the EAA (N), Primary Diluter Orifice Indexer (D), and Sound Enclosure (M).

modification of the extracted exhaust particles. The flow through the extraction nozzles was, therefore, limited to a local Mach number of 0.8. Extracted sample flow ranged from 0.9 std. m^3/hr to 4.8 std. m^3/hr for engine power setting from idle to take-off.

With the exception of the EAA, the sampler is designed for operation in close proximity to an operating turbine engine. All functions of the sampler, therefore, are remotely controlled from a centralized control panel that can be located up to 7.5 m from the filtration units in a safe location such as the test cell control room. The EAA continuously malfunctioned in the test cell environment despite efforts to provide a suitable sound protection enclosure. As a result, the EAA is operated in the test cell control room.

Figure 5 illustrates a typical layout for the FAA-IITRI sampler in an engine test cell. Figure 6 shows the arrangement at United Airlines.

An operations manual for the sampler is available from the FAA.[11]

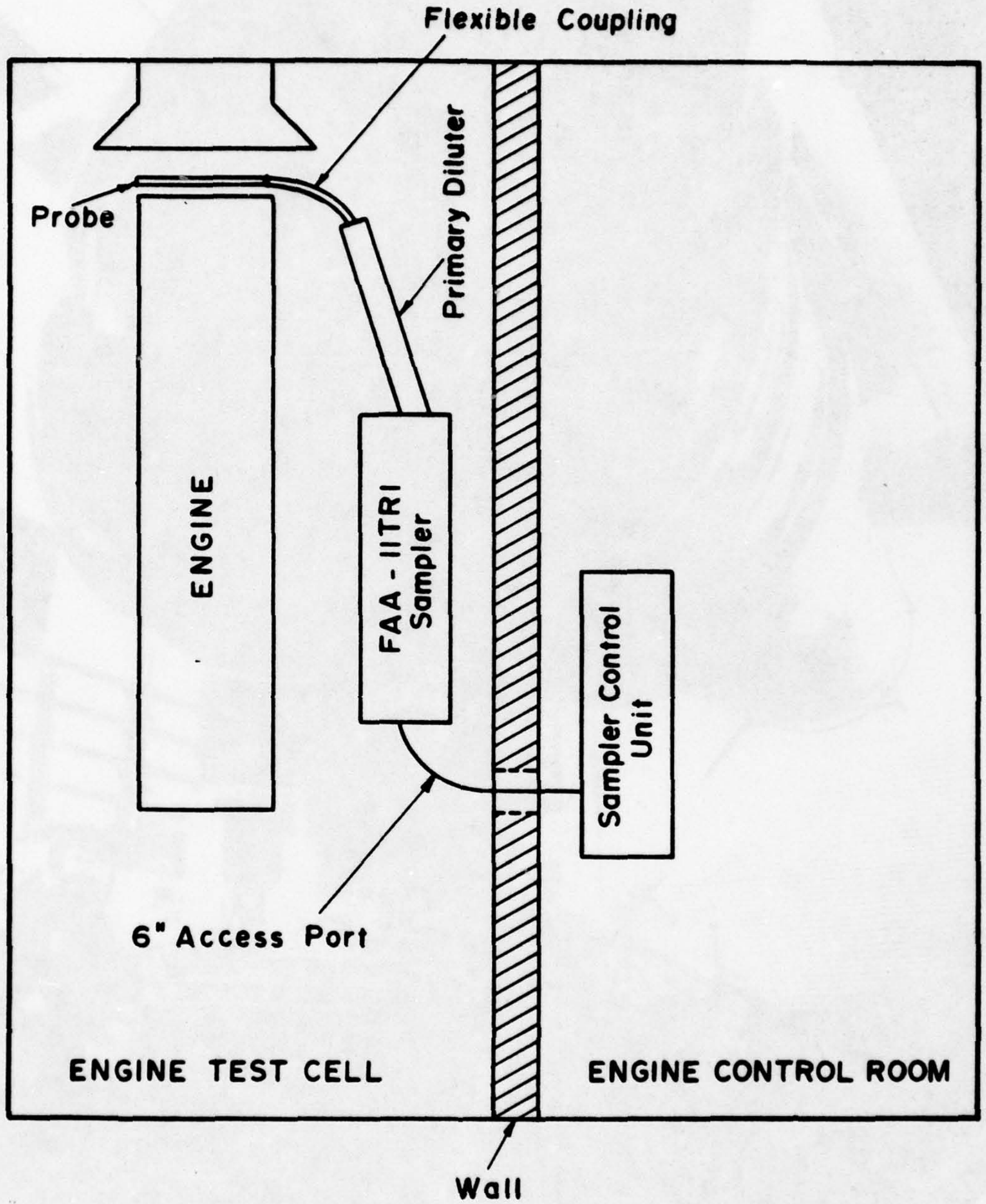


Fig. 5 – Typical layout for FAA – IITRI sampler in an engine test cell

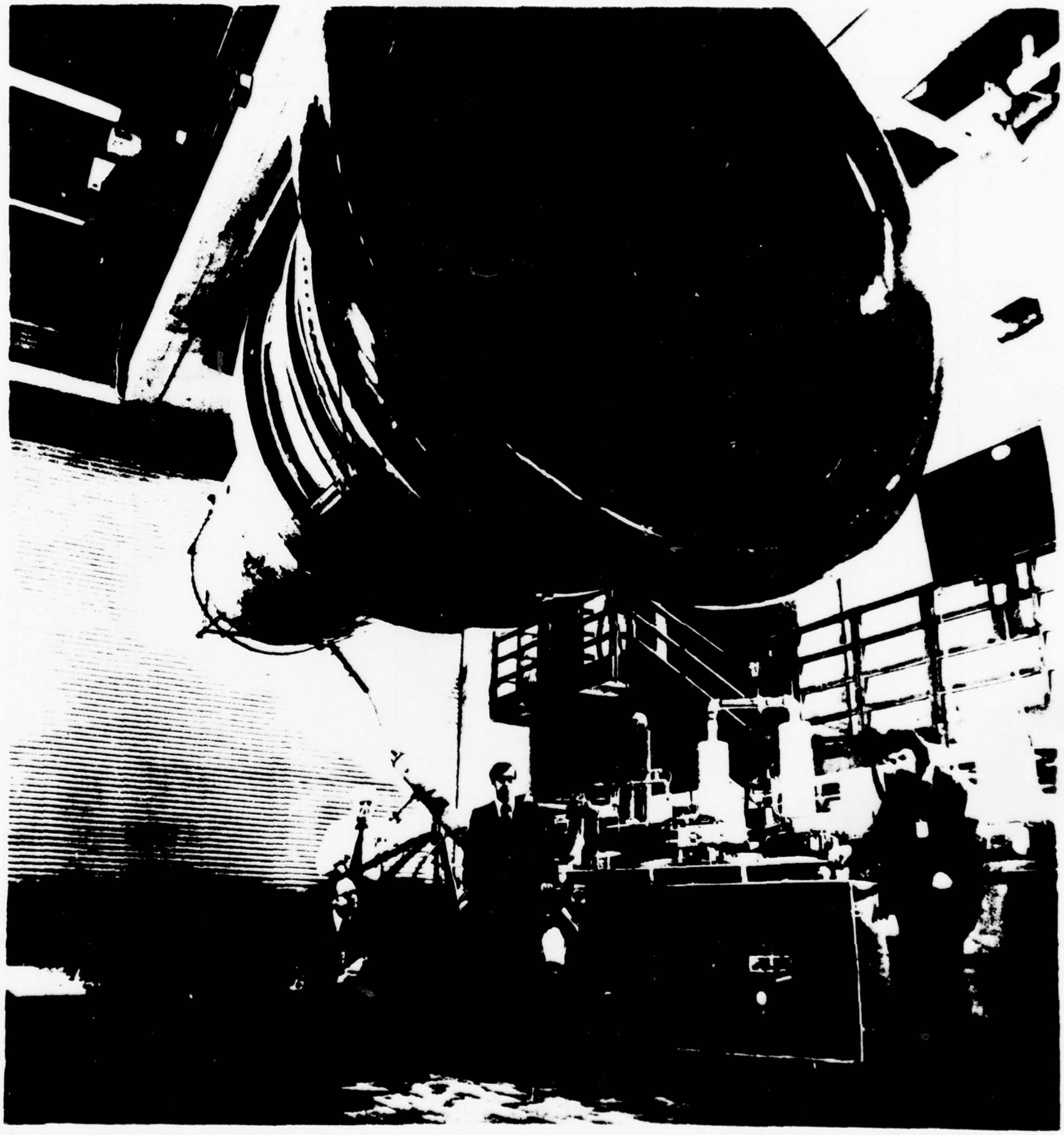


Fig. 6. View of FAA-IITRI Sampler in Engine Test Cell.

3. TEST FACILITIES AND PROCEDURES

3.1 Test Cell Facilities for JT8D and JT9D Engine Tests

Aircraft turbine engines and test cell facilities at United Airlines' Maintenance Operations, San Francisco, California, were used to collect emission samples for characterization.

UAL's Test Cell 3 was used for JT8D engine tests. Test Cell 3 was designed by Albert Kahn Associates of Detroit, Michigan and completed in 1963. The cell has a vertical inlet with turning vanes. The total cell length is 64 feet (19.5 m). An augumentor tube collector is used with a baffled vertical exhaust stack. The thrust bed is ceiling mounted with a quick disconnect frame for engine adaption to the thrust bed. Individual adaptor frames are used for each engine type. Cell 3 can test engines up to 25,000 lbs thrust (111.2 kn).

Test Cell 5 was designed by Aero Systems Engineering of St. Paul, Minn. and completed June 1976. The cell was designed for engines up to 100,000 lbs thrust (444.8 kn) but the current load cell is limited to 60,000 lbs thrust (266.9 kn). Test Cell 5 has a vertical inlet with turning vanes and baffles. An 11 ft. (3.35 m) diameter augmentor tube type collector is used with a vertical acoustic lined exhaust. The thrust bed is ceiling mounted and uses a quick disconnect frame adaptor for engine attachment. The cell has a hydraulic platform built into the floor to lift the engine up to the thrust bed.

Both test cells feed all performance data into an IBM 1800 computer, which records the observed data and corrects it to standard day conditions. Both observed and corrected data is printed at the operator station for comparison with actual console instrumentation.

Both cells utilize an engine preparation room for installation of the thrust bed adaptor and necessary instrumentation. In this way, only about 20 minutes are required to hang the engine in the cell and remove the transport stand.

3.2 Description and History of the Engines Tested

The JT8D engine is a Pratt & Whitney turbofan engine with a 1:1 by-pass ratio. Engines from two models, the JT8D-7 and the JT8D-15, were represented in the tests. The models are identical in exterior and interior dimensions, but the JT8D-15 provides an additional 6.7 kn of thrust by running the engine at higher rpm to increase air flow and at higher temperatures. Combustor systems are identical with the fuel nozzles interchangeable between models. The combustors are identical except for the mounting lug which holds the head in position within the engine. The turbines are different in that the higher temperatures of the JT8D-15 at full power requires air cooled first-stage turbine blades. The JT8D-7 uses uncooled solid first-stage turbine blades. The gas generator of the JT8D-7 has a maximum pressure ratio of 16.2:1 while the JT8D-15 has an 18:1 pressure ratio.

The JT9D-3A engine is a Pratt & Whitney turbofan engine with a 5:1 by-pass ratio. The gas generator has a maximum pressure ratio of 22:1 and a turbine inlet temperature of 2300°F (1260°C).

Additional data on the JT8D and JT9D engines are given in Table 3.

Table 3

DESCRIPTION OF JT8D AND JT9D TURBOFAN ENGINES

	JT8D-7	JT8D-15	JT9D-3A
Max. Thrust, lbs	14,000	15,500	43,500
kn	62.3	69	193.6
Total Air flow, lbs/sec	315	324	1,520
kg/sec	143	147	690
Weight, lbs	3,156	3,310	8,630
kg	1,432	1,502	3,920

JT8D and JT9D engines were selected on the basis of availability at the time emission tests were scheduled. Therefore, different engines were tested and their selection was based on UAL's fleet requirements. Represented in the test series were two JT8D-7, two JT8D-15, and four JT9D-3A. The maintenance history of the individual engines tested is given in Tables 4 and 5.

The TF30-P-1 engine tested was a non-fleet engine provided by the FAA and tested in their NAFEC test cell facilities. Its maintenanence record and history are unknown. The TF30 engine is the military version of the JT3D. It represents engine technology prior to the smoke reduction programs of the U.S. engine manufacturers.

Table 4

ENGINE MAINTENANCE HISTORY - JT8D ENGINES

(a) Maintenance Performed

Model	Serial Number	Maintenance Performed
JT8D-7	654957	Overhauled (0 hrs TSO) Fuel nozzles and combustors.
JT8D-15	648796	Overhauled (0 hrs TSO) Fuel nozzles and combustors.
JT8D-7	648735	Part time fuel nozzles (870 hrs TSO) and combustors (5 each 870 hrs TSO, 2 each 5214 hrs TSO and 2 each 5678 hrs TSO).
JT8D-15	696572	New engine, only time on it is Pratt & Whitney test cell and emission run.

(b) Maintenance Record

Model	Serial Number	Engine Total Time	N_1C TSO/HM	N_2C TSO/HM	1st NGV TSO/HM	N_1T TSO/HM	N_2T TSO/HM
JT8D-7	654957	21,078	23,062	20,960	0	25,658	8,025
			12,765	8,025	0	8,406	"
JT8D-15	648796	30,382	16,475	26,140	0	24,230	0
			10,537	8,588	0	12,711	0
JT8D-7	648735	28,521	18,506	25,914	870	11,476	5,214
			"	11,386	"	7,938	"
JT8D-15	696572	0	0	0	0	0	0

TSO = Time in hours since overhaul
HM = Time in hours since heavy maintenance inspection
N_1C = Low pressure compressor
N_2C = High pressure compressor
1st NGV = First-stage high pressure turbine nozzle
N_1T = Low pressure drive turbine
N_2T = High pressure drive turbine

Table 5

ENGINE MAINTENANCE HISTORY - JT9D-3A Engines

(a) Maintenance Performed

Serial Number	Maintenance Performed
662734	Overhauled fuel nozzles, combustor 1816 hrs since overhaul (TSO).
663031	Combustor - Overhauled, fuel nozzles 4025 hrs since overhaul.
663082	Fuel nozzles - 2122 hrs since overhaul, combustor 3943 hrs TSO but 0 time since Heavy Maintenance Inspection.
662794	Fuel nozzles and combustor overhauled (0 hrs TSO)

(b) Maintenance Record

Serial Number	Engine Total Time	Fan *TSO/HM	N_1C TSO/HM	N_2C TSO/HM	1st NGV TSO/HM	N_1T TSO/HM	N_2T TSO/HM
662734	20,396	15,700	18,017	18,323	3,810	13,294	19,096
		"	"	10,103	0	0	15,793
663031	17,651	18,677	22,086	18,064	0	18,265	17,935
			"	13,674	0	0	0
663082	17,140	2,122	18,726	18,205	4,075	18,195	20,855
		"	14,208	18,205	0	14,548	16,727
662794	19,533	0	18,621	17,621	0	19,133	19,410
		"	0	"	0	0	0

See Table 4 for nomenclature and symbols.

3.3 Fuel Selection and Analysis

3.3.1 Fuel Selection

During the early planning for the particulate emissions tests it became apparent that the test period would likely fall during a time when Alaska North Slope crude would be arriving on the West Coast and that this could introduce considerable variability in the batch-to-batch characteristics of product delivered to UAL's Maintenance Operations Center fuel system through normal pipeline channels. It was recognized also that it would be extremely difficult to exercise any effective control over the characteristics of fuel on which any given series of tests were run and that there might be considerable difference between the fuels for successive tests on a given engine type or for different engine types. This introduced the possibility that different fuel batches with widely varying burnability might be introduced as an uncontrolled variable in the test program.

Cost alone precluded the use of a controlled fuel source for these tests. This situation was discussed with Mr. R. W. Schirmer of Phillips Petroleum Company during a visit to the Phillips Research Laboratories, Bartlesville, Oklahoma, in early 1976. As a result of these discussions, use of two products, first a referee JP-5 (segregated source of fuel from one batch) and a cyclo-paraffin JP-5 meeting the Military RP-1 Specification was considered. Price quotations were received for both of these fuels and after discussion with the FAA it was concluded that the tests should be run on the normal "house brand" fuel, hereafter referred to as Jet A, available through the normal distribution channels and stocked in MOC fuel tanks, and the cyclo-paraffin JP-5 available commercially under the trade name Pearl Kerosene and hereafter referred to either as Pearl Kerosene or as "PK".

3.3.2 Jet A Fuel

United Airlines' Jet A fuel is procured to Specification FUE 4500-7 with detail requirements as shown in Table 6. Detail

Table 6

DETAILED REQUIREMENTS FOR JET A AND RP-1 FUELS

Specification	UA FUE 4500-7 Nov. 1976 JET A	MIL-P-25576C Nov. 1967 RP-1
Acidity, total max, mg KOH/g	0.1	
Aromatics, vol, max, %	25	5
Sulfur, Mercaptan, cwt, max, %	0.003	0.005
Sulfur, total wt, max, %	0.3	0.05
Distillation temperature, °F (°C):		
10% Recovered, max. temp.	400 (204.4)	365-410
20% Recovered, max. temp	. . .	. . .
50% Recovered, max. temp.	Report	Report
90% Recovered, max. temp.	Report	Report
Final boiling point, max, °F (°C)	572 (300)	525
Distillation residue max, %	1.5	1.5
Distillation loss, max, %	1.5	1.5
Flash point, min, °F (°C)	100 (37.8)	110
Gravity, max, °API (min, sp gr) at 60°F	51 (0.7753)	45 (.801)
Gravity, min, °API (max, sp gr) at 60°F	37 (0.8398)	42 (.815)
Vapor pressure, max, lb	. . .	. . .
Freezing point, max (°C)	(-40) Jet A	-36
Viscosity -30°F (-34.4°C) max, cSt	15	16.5
Net heat of combustion, min, Btu/lb.	18400	18500
Combustion properties; one of the following requirements shall be met:		
(1) Luminometer number, min or	45	. . .
(2) Smoke point, min or	25	25
(3) Smoke point, min	18	. . .
Naphthalenes, vol, max, %	3	. . .
Corrosion, Cu strip 2 h at 212°F max	No. 1	1
Thermal stability: one of the following requirements shall be met:		
(1) Filter press. drop, max, in.Hg	3	. . .
Preheater deposit less than	Code 3	. . .
(2) Filter press. drop, max, mm Hg	25	. . .
Tube deposit less than	Code 3	. . .
Existent gum, mg/100 ml, max	7	7
Water reaction:		
Separation Rating	2	. . .
Interface Rating, max	1b	1b
Potential Gum	. . .	14

requirements shown in Table 6 of this specification are consistent with those in ASTM Standard specification for Aviation Turbine Fuels D-1655-75 as published in the 1976 ASTM Book of Standards. United accepts product to a maximum aromatic content of 25 volume percent and smoke point to a minimum of 18. This fuel is typical of that in widespread commercial use for the past several years in domestic United States' operations.

3.3.3 Pearl Kerosene (PK) Fuel

The Pearl Kerosene was procured from the El Segundo Refinery of Chevron USA as a commercial product under the Pearl Kerosene trade name. This is a highly paraffinic, clean-burning kerosene meeting the requirements of Military Specification MIL-P-25576C Grade RP-1 referred to as a "Narrow Cut Kerosene". Detail requirements for this specification are also shown in Table 6. This fuel is characterized by very low aromatic content, high smoke point, and high hydrogen content. While this fuel was used to a limited extent during early jet operations, it is available today in relatively small quantities and could not be considered as a replacement for Jet A fuel in commercial operations because of limited availability. Production batches from the El Segundo Refinery are very consistent and this fuel has the added advantage of being highly reproducible in the event that any further test work became desirable and it was wished to duplicate this fuel.

3.3.4 Fuel Analysis

Table 7 shows the analyses of the fuels used on the program and the engines in which the fuels were burned. The analyses were performed by Chevron U.S.A. Table 8 shows the United Airlines' data bank of refinery inspection data for production Jet A fuels during the first quarter of 1978; the minimum/maximum and average values are shown. To this has been added the analysis for the two samples of fuel used during the emission tests on January 9 and 10, 1978. Comparison of the detail points for the samples taken on these two days indicates very close agreement, within normal test precision, for all of the normal production require-

Table 7

ANALYSES OF JET FUELS BY CHEVRON, USA

DATE:	1/9/78	1/10/78	4/20/78	4/24/78
FUEL TYPE:	JET A	JET A	JET A	JET A
ENGINE:	662734	654957	663031	648796 & 648735
Gravity, API	41.3	41.4	41.6	42.0
Flash Point, Tag Closed Cup; ^{o}F	120	126	118	118
Color & Appearance (Visual)	Clear & Uniform	Clear & Uniform	Clear & Uniform	Clear & Uniform
Color, Saybolt	+5*	+3*	0*	+0*
Viscosity at -30^{o}F; cs	9.40	9.37	8.44	8.10
Distillation; ^{o}F:				
IBP	348	348	340	338
10% Recovered	380	380	371	368
50% Recovered	430	427	422	419
90% Recovered	485	483	475	476
End Point	523	519	522	519
Residue; Vol. %	1.0	1.0	1.0	1.0
Loss; Vol. %	1.0	1.0	1.0	1.0
Total Acid No.; mg KOH/g	0.01	0.01	0.01	0.01
Aromatics, Vol. %	20	19	17	20
Olefins; Vol. %	1	1	2	1
Sulfur, Mercaptan; Wt. %	0.0002	0.0004	0.0003	0.0004
Sulfur; Wt. %	0.081	0.098	0.087	0.101
Freezing Point; ^{o}F	-55	-52	-57	-55
Heating Value, Aniline-Gravity Product	5,633	5,647	5,695	5,674
Hydrogen Content; %	12.80	13.41	13.54	13.65
Smoke Point, mm	20	20	21	20
Copper Strip, Corrosion; 2 hr. @ 212^{o}F	1A	1A	1A	1A
Thermal Stability				
Filter Pressure Drop; mm of Hg	0	0	0	0
Heater Tube Deposits; Code No.	1	1	1	1
Gum Existent, Steam-Jet; mg/100 ml	1	1	1	2
Water Reaction:				
Interface Rating	1B	3*	1B	1B
Separation Rating	0 ml	0 ml	0 ml	0 ml
Particulate Contamination, mg/1	0.7	1.1	0.8	0.9
Naphthalene Content; % (D1840)	2.2	1.7	1.6	2.2

* Off Test

Table 7 (cont.)

ANALYSES OF JET FUELS BY CHEVRON, USA

DATE:	6/20/78	6/21/78	6/22/78	4/25/78
FUEL TYPE:	JET A	JET A	JET A	PEARL K
ENGINE:	696572	663082	662794	648796 & 663031
Gravity, API	41.5	40.9	40.9	44.7
Flash Point, Tag Closed Cup; ^{o}F	118	116	120	150
Color & Appearance (Visual)	Clear & Uniform	Clear & Uniform	Clear & Uniform	Clear & Uniform
Color, Saybolt	+4*	+1*	+1*	+30
Viscosity at -30^{o}F; cs	7.99	8.25	8.16	8.45
Distillation; ^{o}F				
IBP	332	334	333	367
10% Recovered	362	364	364	375
50% Recovered	420	422	424	389
90% Recovered	476	477	479	435
End Point	524	523	527	504
Residue; Vol. %	1.0	1.0	1.0	1.0
Loss; Vol. %	1.0	1.0	1.0	1.0
Total Acid No.; mg KOH/g	0.01	0.01	0.01	0.01
Aromatics, Vol. %	20	20	20	1
Olefins; Vol. %	2	1	1	1
Sulfur, Mercaptan; Wt. %	0.0003	0.0002	0.0003	0.0001
Sulfur; Wt. %	0.108	0.105	0.098	0.010
Freezing Point; ^{o}F	-58	-59	-57	-66
Heating Value, Aniline-Gravity Product	5,540	5,370	5,366	6,991
Hydrogen Content; %	13.05	13.45	13.46	14.25
Smoke Point; mm	20	20	20	35
Copper Strip, Corrosion; 2 hr. @ 212^{o}F	1A	1A	1A	1B
Thermal Stability				
Filter Pressure Drop; mm of Hg	0	0	0	0
Heater Tube Deposits; Code No.	1	1	1	1
Gum Existent, Steam-Jet; mg/100 ml	1	1	1	1
Water Reaction;				
Interface Rating	1B	1B	1B	1B
Separation Rating	0 ml	0 ml	0 ml	0 ml
Particulate Contamination; mg/l	0.2	0.8	0.5	0.2
Naphthalene Content; % (D1840)	2.2	2.3	2.5	0.1

* Off Test

Table 8

FIRST QUARTER JET A FUEL ANALYSIS
June 21, 1978

Fuel	Date	API	Distillation IBP	10%	50%	90%	END	Fz Pt	Fla Pt	Visc	BTU /lb	BTU /Gal	Anil Grav	Tot Acid	Tot Sulf	Merc	Coker PR	Coker TU	Gum Ex	Water App	Water Sep	Arom	Oil	NA	Sm Pt	Hydrogen Calc	Hydrogen Meas
JET A	(Min)	40.2	298	347	386	440	491	-44	106	5.6	18488	124646	5381	.010	0.03	.001	0.0	-	0.1	--	0.0	15.0	1.0	0.4	19.0	13.51	
	(Max)	44.4	350	396	450	508	566	-85	130	10.1	18599	127365	6000	.030	0.18	.002	0.0	-	0.2	--	0.0	22.0	4.0	3.0	25.0	13.81	
	(Avg)	41.6	317	368	424	483	526	-56	117	7.9	18525	126317	5674	.022	0.11	.001	0.0	-	0.1	--	0.0	19.0	1.4	1.9	20.8	13.61	
JET A	1/9/78	41.3	348	380	430	485	523	-55	120	9.4	18532	------	5633	.01	.08	.0002	0.0	1	1.0	1B	---	20.0	1.0	2.2	20.0	13.57	12.80
	1/10/78	41.4	348	380	427	483	519	-52	126	9.4	18535	------	5647	.01	.09	.0004	0.0	1	1.0	1B	---	19.0	1.0	1.7	20.0	13.60	13.41

Table 9

SECOND QUARTER JET A AND PK FUEL ANALYSIS
September 23, 1978

Fuel	Date	API	Distillation IBP	10%	50%	90%	END	Fz Pt	Fla Pt	Visc	BTU /lb	BTU /Gal	Anil Grav	Tot Acid	Tot Sulf	Merc	Coker PR	Coker TU	Gum Ex	Water App	Water Sep	Arom	Oil	NA	Sm Pt	Hydrogen Calc	Hydrogen Meas
JET A	(Min)	39.4	294	346	401	444	486	-47	109	5.7	18418	125576	5017	.002	0.03	.001	0.0	-	0.0	--	0.0	12.0	1.0	0.7	18.0	13.36	
	(Max)	43.2	332	376	432	497	551	-71	128	9.1	18786	127794	5897	.020	0.13	.004	0.0	-	0.2	--	0.0	23.0	3.0	3.0	23.0	13.86	
	(Avg)	41.0	319	363	421	476	528	-57	120	8.1	18512	126719	5488	.014	0.07	.001	0.0	-	0.1	--	0.0	18.9	1.4	2.1	20.2	13.54	
JET A	4/20/78	41.6	340	371	422	475	522	-57	118	8.4	18545	------	5695	.01	0.09	.0003	0.0	1	1.0	1B	---	17.0	2.0	1.6	21.0	13.65	13.54
	4/24/78	42.0	338	368	419	476	519	-55	118	8.1	18532	------	5674	.01	0.10	.0004	0.0	1	1.0	1B	---	20.0	1.0	2.2	20.0	13.58	13.65
	6/20/78	41.5	332	362	420	476	524	-58	118	8.0	18518	------	5540	.01	0.11	.0003	0.0	1	1.0	1B	---	20.0	1.0	2.2	20.0	13.54	13.05
	6/21/78	40.9	334	364	422	477	523	-59	116	8.3	18508	------	5370	.01	0.11	.0002	0.0	1	1.0	1B	---	20.0	1.0	2.3	20.0	13.50	13.45
	6/22/78	40.9	333	364	424	479	527	-57	120	8.2	18510	------	5366	.01	0.10	.0003	0.0	1	1.0	1B	---	20.0	1.0	2.5	20.0	13.50	13.46
	(Avg)	41.4	335	366	421	477	523	-57	118	8.2	18522	------	5529	.01	0.10	.0003	0.0	1	1.0	1B	---	19.0	1.0	2.2	20.0	13.55	13.43
PK	4/25/78	44.7	367	375	389	435	504	-66	150	8.5	18708	------	6991	.01	0.01	.0001	0.0	1	1.0	1B	---	1.0	1.0	0.1	35.0	14.36	14.25

See Nomenclature and Table 7 for notations.

ments. To this has been added calculated hydrogen according to ASTM Method D3343. Measured hydrogen values reported by Chevron are also shown. There is considerable discrepency from the calculated values for the January 9 sample. The calculated values for these two samples conform closely to those for other fuel batches produced in this same time period. This discrepancy between the measured and calculated hydrogen values is of such a magnitude as to cast doubt upon the validity of the measured values and it is recommended that the calculated values be used exclusively.

Table 9 contains data for the second quarter of 1978 during which the majority of the Jet A and PK fuel samples were taken. Average values are shown for these five samples. Data for the single PK sample taken on April 25, 1978, are also shown at the bottom row of Table 9.

Inspection of the analysis reports for the 7 Jet A samples indicates a high degree of consistency with data for other production batches produced just prior to the sample dates for these test fuels. The gravity values are extremely close with an average of 41.4° API for the 7 Jet A samples compared with 41.0° for the second quarter. Average distillation values for the initial boiling point shows somewhat higher value for the test fuels than would be expected but this is not considered to be a significant difference. Other distillation values agree very closely. The parameters of principal interest from a burnability standpoint, aromatic content, naphthalene content, and smoke point for the test fuels show good consistency with the refinery average.

The only significant variation from the average of 19 percent aromatic content and 20 smoke point appears in the April 20, 1978, sample showing 17 percent aromatics and 21 smoke point. These values are very consistent in consideration of the possible variation. For example, during this time period minimum aromatic content as low as 12 percent was noted together with a maximum of 23 percent. Likewise, the range in smoke point actually experienced of one millimeter was very modest compared to the 5 millimeter range noted in the other refinery samples. Comparison of the hydrogen

values again shows the discrepancy between calculated and measured values noted previously. Again, the calculated values are highly consistent and show reasonable batch-to-batch variability with limits of +0.10 percent and -0.05 percent from the average for the five samples. Similar values for the measured hydrogen for the five fuel samples show variation of +0.22 percent and -0.38 percent from the average value. A recent ASTM study of precision of the three data sources, i.e., calculated per D-3343, combustion, and the nuclear magnetic resonance "NMR" test now undergoing standardization activities within ASTM, show the following relationship relative to accepted true value.

NMR	+0.03%
Combustion	-0.03%
Calculated	-0.08%

This relationship is further evidence that the measured hydrogen values produced by the combustion method are suspect. The measured values are, on the average, 0.12 percent below the calculated values whereas the accepted statistical study indicates that they should be 0.05 percent higher than the calculated values.

Comparison of average values for the five test fuels with the results for the Pearl Kerosene shows the expected differences between these two fuels. The PK sample is somewhat lighter in gravity and shows a definitely flatter distillation curve. Flash point is appreciably higher at 150°F relative to the average of 118°F for Jet A samples.

Heating value is also appreciably higher. The values for burnability of 1 percent aromatics, 0.1 percent naphthalenes and 35 smoke point indicate the improved burning characteristics by conventional test methods compared to the comparison with the average values per the Jet A of 19 aromatic content, 2.2 percent naphthalenes and 20 smoke point. The hydrogen data also indicate the expected difference with calculated value of 14.36 compared to the average of 13.55 for the Jet A fuels.

3.4 Test Procedures

Emission testing on the JT8D and JT9D turbofan engines were conducted at UAL's San Francisco's Maintenance Facilities January 9-10, 1978, April 20-25, 1978, and June 20-22, 1978. Prior to testing, the local air pollution control authority was notified and permission received to operate the engines without the addition of a smoke reducing agent to the fuel. Five power settings, idle, approach, cruise, climbout, and takeoff, were studied. Settings were based on the engine pressure ratio (EPR) values. In January, the desired power settings were approached from lower values. In the April and June tests, the desired power settings were approached from higher values. The change was made after discussions with the FAA revealed that the descending approach provides data with less variability and greater validity.

After the engine was mounted in the test cell and readied for testing, the FAA-IITRI particulate matter sampler was affixed and connections made to the required utilities. The operation of the sampler was checked by sequencing it through its operational cycle several times to insure that all functions were operational. A leak check was made; the flowmeters and orifices were calibrated. The EAA was turned on and calibrated according to procedures stated in its procedure manual. The sampling turrets were loaded with filters and personnel in the test cell evacuated; the test cell operator was then signalled to start the engine. The engine operation was stabilized at each power setting before sampling started. The following procedure was used for all power points except takeoff on the JT8D-7 and JT9D-3A engines.

A. The desired EPR was set.

B. The engine exhaust gas temperature was allowed to stabilize at the power point.

C. After the gas temperature was stable for one minute, sample collection started.

D. The elapsed time from when power was set until sampling began was 2½ to 3 minutes.

E. Sampling times varied with power settings.

F. After completion of the sampling, the engine was adjusted to the next desired power point and allowed to stabilize.

Operating time at takeoff for the engines was limited to 5 minutes, less than the time required to acquire sufficient sample for characterization and mass emission determination. Therefore, the engines had to be recycled. The following procedure was used at takeoff for the JT8D-7 and JT9D-3A engines.

A. The engine was allowed to stabilize for one minute. The exhaust gas temperature would stabilize within this time.

B. Acquision of the sample was started.

C. A 3-minute sample was taken. Power was held until the sampler was cycled to the by-pass position, then reduced.

D. After a 2-minute cool-down, the procedure was repeated until sampling was complete.

The JT8D-15 engines were operated at the JT8D-7 power ratings. This made the test conditions common. The JT8D-15 engines did not need to be recycled when operated at the JT8D-7 takeoff power point.

3.5 Test Schedule and Test Matrix

Sampling times for the JT8D and JT9D engines was estimated based on the knowledge gained by sampling the TF30 engine. However, the JT8D and JT9D engines emitted much less particle matter than anticipated and sampling times had to be adjusted to acquire valid data. Since funding was limited not all power settings could be sampled for each engine and a test matrix was established to maximize the information content of the data. The matrix is given in Table 10.

3.6 Analytical Methods

3.6.1 Mass Emission Rate

The mass emission rate of the engines was determined by gravimetric analysis. Gelman, type AE, glass fiber filters, 142 mm in diameter were weighed on an analytical balance before and after sample collection. The tare weights were corrected for shifts in

Table 10

TEST MATRIX AND SAMPLING TIMES FOR THE JT8D and JT9D ENGINE EMISSION TESTS

Date	Engine Type	Engine Ser. No.	Fuel	Type of Sample*	Sampling Time, Minutes — Engine Power Setting: Idle	Approach	Cruise	Climbout	Takeoff
1/9/78	JT9D-3A	662734	JET A	MASS	15	5	4	3	2
				EM	10	10	7	5	3
				EAA	3	3	3	3	3
1/10/78	JT8D-7	654957	JET A	MASS	15	5	4	3	2
				EM	10	10	7	5	3
				EAA	3	3	3	3	3
4/20-21/78	JT9D-3A	663031	JET A	MASS		20			12
			& PK	EM		20			9
				EAA		3	3	3	3
4/24-25/78	JT8D-15	648796	JET A	MASS		20	10	6	6
			& PK	EM	7	5	5	3	4
				EAA	3	3	3	3	3
4/25/78	JT8D-7	648735	JET A	MASS		20	10	6	6
				EM	7	5	5	3	4
				EAA	3	3	3	3	3
6/20/78	JT8D-15	696572	JET A	MASS		20	10	6	6
				EM	7	5	5	3	4
				EAA	3	3	3	3	3
6/21/78	JT9D	663082	JET A	MASS		25			
				EM	14	20		10	
				EAA		3		3	
6/22/78	JT9D	662794	JET A	MASS				30	
				EM			25	10	
				EAA			3	3	

* MASS -- Sample collected for the gravimetric determination of mass emission rate.

EM -- Sample collected for particle characterization by electron microscopy and image analysis.

EAA -- Electrical Aerosol Analyzer data.

weights due to humidity effects with control filters. For the April and June tests the control filter's average weight shift was zero with a maximum shift of ± 0.1 mg. In January, the control filters used for the JT8D test lost an average of 1.2 mg while the control filters used for the JT9D tests lost an average of 2.6 mg. Therefore, the corrections applied during the January tests account for a significant portion of the weight increase reported and the data must be viewed cautiously.

The calculation of the emission rate proceeded as follows:

$$\frac{W_s}{t_s} \times \frac{W_a}{W_{as}} = \text{Emission rate, lbs/hr}$$

Where: W_s = weight of particles collected on filter, lbs

t_s = sampling time, hrs

W_a = mass flow rate of engine air either primary or total depending on engine configuration, lbs/sec

W_{as} = mass flow rate of sample, lbs/sec

3.6.2 Electron Microscopy

The electron microscope used in this study was a JEM 100C scanning transmission electron microscope (JEOL, Incorporated, Medford, Massachusetts). The resolution of the microscope is 0.45 nm in the SEM mode. The microscope has the added capability of energy dispersive X-ray detection for elemental analysis. The X-ray detector is a KEVEX unit (KEVEX Corporation, Burlingame, California) with a resolution at 5.9 KEV of less than 159 eV @ 1 KHz. The X-ray analyzer is a Tracor/Northern NS 880 system (Tracor Northern, Incorporated, Middleton, Wisconsin). The samples collected for particle analysis were examined in the secondary electron emission (SEM) mode of the microscope.

The 0.03 μm pore size Nuclepore[R] filters used for sample collection were returned to the electron microscope laboratory in

sealed Petri dishes. Several squares, 1 cm x 1 cm, were cut from the filter at midradius, taped to a glass microscope slide and a thin conductive film applied in a JEOL vacuum evaporator. For X-ray analysis, a carbon film was applied; for particle sizing a gold film was used.

Elemental analysis of the emission particles was performed using the energy dispersive X-ray spectrometer and the NS 880 analysis systems. The X-ray spectrometer is limited to the detection of elements with atomic numbers above 11 (Na). Thus Li, Be, B, C, N, and F are not detected. The detectability limit of the system is approximately 0.1% or 1000 ppm. It can, however, detect concentration levels of 10^{-15} grams for the elements above sodium. The Mg and Si content of mineral fibers, $Mg_3Si_2O_5(OH)_4$, of size 0.03 x 0.24 μm with an approximate mass of 4.4 x 10^{-10} μg are routinely measured by the instrument at 30,000X, the magnification used for particle sizing.

Particles of various sizes and shapes were examined and no elements were detected. The assumption, therefore, is made that the particles emitted by the turbofan engines tested are essentially carbonaceous in composition.

The gold coated filter segments were examined under the microscope in the SEM mode. Photographs were taken at 10,000X, 20,000X, 30,000X, 60,000X, and occasionally at 100,000X. For particle analysis 30,000X provided the best compromise between resolution and number of particles per field. High contrast photographs were taken on 10 cm x 12.7 cm P/N Polaroid film and integrated by the Quantimet 720 Image Analyzer (Image Analyzing Computer, Ltd., Cambridge, England). Negatives are used for analysis while the positives are used for reports and displays. A minimum of 15 fields (photographs) or enough fields to contain 400 particles were taken for particle analysis.

3.6.3 <u>Image Analysis for Particle Size and Shape</u>

The Quantimet 720 Image Analyzing Computer measures and classifies selected features of an image formed by optical and

electron microscopes. It can utilize photographic positives or negatives taken of the images formed by both instruments. The optical image is converted to electrical pulses. The electrical pulses are subsequently analyzed to generate quantitative image formation. For this study, a negative of an electron photomicrograph was placed on a specially designed light box known as an epidiascope. The negative was inverted onto the epidiascope, and using transmitted light, the image was projected onto a CRT. The operator therefore views the image on the screen as it appears on the photograph, instead of dealing with a mirror image. The needed parameters of the image are then ready to be computed.

The Q-720 measures various parameters in units of picture points (pp). To calibrate the instrument, a ruler is placed on the epidiascope, and the corresponding frame size in pp's is aligned with the rulings. For the arrangement used in this study 508 pp equalled 3 cm @ 30,000X. Therefore, 508 pp equals 1 μm or 1 pp equals 0.002 μm and 1 pp^2 represents an area of 0.000004 μm^2. The area and perimeter of each particle were measured in picture points. The diameter of the particle was computed from a sphere of area equal to the particle. The formula area/$perimeter^2$ yielded the shape factor. To avoid repeating a measurement, each particle was circled on the photograph after its area and perimeter were recorded.

4. TEST RESULTS AND DISCUSSIONS

4.1 Test Results

Performance data for the TF-30, JT8D, and JT9D engines are presented in Tables 11, 12, and 13. Given are data on the engine pressure ratios (EPR), temperatures at various points in the engine, total (W_{at}) and primary or core (W_{ap}) air flows, fuel flow (W_f), fuel to primary air ratio (F/A_p), thrust, and thrust specific fuel consumption (TSFC) for each engine and power setting tested. The SAE smoke numbers are given for TF-30 engine.

Emission data for the TF-30, JT8D, and JT9D engines are given in Tables 14, 15, and 16. Shown is the sampling information for the collection of the particulate emissions for the determination of the mass emission rates, the calculated mass emissions, the geometric mean particle diameter, d_g, and the geometric standard deviation (σ_g) of the particle size distribution obtained by electron microscopy and image analysis, and the particle concentration data obtained by the Electrical Aerosol Analyzer (EAA).

The mass emission data in kg/hr were calculated from the formula:

$$\text{Emission Rate, kg/hr} = 3.604 \frac{M_c W_a}{\rho W_s \Delta t}$$

Where:

M_c = mass of collected sample, grams

W_a = engine exhaust flow at sampling point, lbm/sec

Δt = sample collection time, min

ρ = mass density of air, 0.07095 lbm/ft³

W_s = sample flow rate, ft³/min

The engine exhaust flow at the sampling point differs with the engine type. For the mixed flow engines, the TF-30 and JT8D engines, total air flow (W_{at}), fan plus primary air, was used in the calculations; for the JT9D engine, primary air (W_{ap}) was used.

Table 11

TF30-P-1 TURBINE ENGINE PERFORMANCE DATA

Date	Power Setting	EPR	Temperature, °F T_1	T_4	T_5	Air & Fuel Flow, lbm/s Wat	Wap	Wf	F/Ap Ratio	Thrust lbf	TSFC lbm/lbf·hr	SAE Smoke Number
6/8/77	Idle	1.08	66	225	907	74	37	0.25	0.0068	1021	0.881	32.9
	Approach	1.33	66	457	1099	143	55	0.65	0.0118	3743	0.621	64.6
	Cruise	1.73	66	615	1573	196	83	1.31	0.0158	7547	0.619	71.1
	Climbout	1.94	66	664	1740	216	107	1.66	0.0155	9307	0.635	76.2
	Takeoff	2.06	66	706	1849	222	115	1.90	0.0166	10318	0.655	76.6
6/9/77	Cruise	1.72	58	631	1576	196	90	1.31	0.0146	7553	0.617	72.0
	Cruise	1.72	59	620	1567	196	91	1.30	0.0143	7523	0.614	70.8
	Cruise	1.73	60	615	1565	197	91	1.31	0.0144	7534	0.618	70.4
	Cruise	1.73	59	618	1569	196	91	1.30	0.0144	7523	0.615	--
6/10/77	Idle	1.08	61	244	918	---	37	0.25	0.0068	1022	0.876	33.2
	Approach	1.33	60	448	1195	142	55	0.66	0.0120	3765	0.627	65.8
	Cruise	1.73	60	608	1576	197	90	1.31	0.0146	7592	0.616	71.2
	Climbout	1.94	58	678	1726	216	106	1.66	0.0157	9323	0.634	71.3
	Takeoff	2.04	56	706	1841	224	114	1.89	0.0166	10325	0.652	--

NOTE: JET A fuel was used in all tests.

Table 12

JT8D TURBINE ENGINE PERFORMANCE DATA

Date	Engine No. & Type	Fuel Type	Power Setting	EPR	Temperature, ^{o}F T_1	T_4	T_5	T_7	Pressure P_{S4}, Atm	Air & Fuel Flow, lbm/s Wat	Wap	Wf	F/Ap Ratio	Thrust lbf	TSFC lbm/lbf·hr
1/10/78	654957	JET A	Idle	1.05	60	270	1240	687	1.04	97	36	0.31	0.0087	1048	1.065
	JT8D-7		Approach	1.22	60	520	1200	653	5.96	185	71	0.66	0.0094	3862	0.615
			Cruise	1.50	59	640	1460	790	9.70	255	103	1.24	0.0120	7759	0.575
			Climbout	1.78	59	735	1630	916	12.68	296	129	1.83	0.0142	11148	0.591
			Takeoff	1.97	59	800	1720	977	14.67	316	143	2.20	0.0152	13069	0.606
4/24/78	648796	JET A	Idle	1.05	56	283	1250	709	1.01	92	30	0.32	0.0107	745	1.546
	JT8D-15		Approach	1.22	56	510	1210	665	5.87	178	69	0.68	0.0099	3736	0.655
			Cruise	1.51	56	640	1480	804	9.70	250	107	1.31	0.0123	7931	0.595
			Climbout	1.78	56	700	1600	918	12.43	288	131	1.86	0.0142	11168	0.600
			Takeoff	1.96	56	800	1720	977	14.24	307	146	2.23	0.0153	13070	0.614
4/25/78	648796	PK	Idle	1.05	60	283	1260	714	1.01	92	31	0.34	0.0110	783	1.563
	JT8D-15		Approach	1.23	59	525	1225	676	6.01	180	71	0.72	0.0102	3846	0.674
			Cruise	1.52	60	640	1510	815	9.77	242	104	1.35	0.0130	7957	0.611
			Climbout	1.78	59	730	1635	923	12.37	288	131	1.87	0.0143	11029	0.610
			Takeoff	1.96	58	775	1725	981	14.24	300	142	2.26	0.0160	13056	0.623
4/25/78	648735	JET A	Idle	1.05	63	270	1230	675	1.01	97	36	0.32	0.0089	1047	1.100
	JT8D-7		Approach	1.22	63	525	1200	650	6.03	184	71	0.67	0.0095	3832	0.629
			Cruise	1.52	62	655	1465	783	9.90	259	104	1.28	0.0123	7871	0.585
			Climbout	1.78	63	735	1625	905	12.71	296	129	1.84	0.0143	11176	0.593
			Takeoff	1.95	61	780	1720	977	14.46	312	142	2.21	0.0156	13067	0.609
6/20/78	696572	JET A	Idle	1.05	61	283	1245	694	1.00	97	35	0.34	0.0097	834	1.468
	JT8D-15		Approach	1.22	62	515	1215	664	5.83	178	69	0.68	0.0099	3722	0.658
			Cruise	1.51	62	644	1480	795	9.69	250	107	1.30	0.0121	8070	0.580
			Climbout	1.76	62	730	1605	891	12.43	289	132	1.83	0.0139	11170	0.590
			Takeoff	1.96	60	780	1700	954	14.42	310	147	2.23	0.0157	13189	0.609

Table 13

JT9D TURBINE ENGINE PERFORMANCE DATA

Date	Engine No. & Type	Fuel Type	Power Setting	EPR	Temperature, °F T_1	T_4	T_5	T_6	T_7	Pressure P_{S4}, Atm	Air & Fuel Flow, lbm/s Wat	Wap	Wf	F/Ap Ratio	Thrust lbf	TSFC lbm/lbf·hr
1/9/78	662734 JT9D-3A	JET A	Idle	1.02	--	886	1080	723	653	3.70	380	54	0.53	0.0098	---	---
			Approach	1.08	--	816	1490	962	755	9.04	720	118	1.48	0.0126	---	---
			Cruise	1.18	--	745	1815	1144	810	13.51	1030	169	2.46	0.0146	---	---
			Climbout	1.31	55	617	2050	1316	914	16.84	1330	210	3.55	0.0169	34270	0.373
			Takeoff	1.42	55	379	2260	1426	986	20.03	1470	236	4.35	0.0184	42668	0.367
4/20/78	663031 JT9D-3A	JET A	Idle	1.02	--	---	--	--	--	---	--	---	--	----	---	---
			Approach	1.08	55	631	1589	995	790	8.65	688	112	1.47	0.0132	12880	0.411
			Cruise	1.18	55	763	1861	1189	858	13.50	1025	168	2.56	0.0152	24987	0.369
			Climbout	1.31	55	848	2064	1332	935	17.42	1335	211	3.57	0.0169	35198	0.365
			Takeoff	1.42	57	908	2289	1458	1004	20.27	1485	239	4.48	0.0188	42959	0.375
4/21/78	663031 JT9D-3A	PK	Idle	1.02	--	378	1070	702	680	3.59	370	52	0.51	0.0098	---	---
			Approach	1.08	56	626	1485	953	756	8.65	700	114	1.45	0.0127	13390	0.390
			Cruise	1.18	56	758	1820	1149	814	13.39	1030	169	2.45	0.0145	24907	0.354
			Climbout	1.31	56	851	2070	1336	925	17.59	1350	214	3.63	0.0169	35933	0.364
			Takeoff	1.41	56	899	2285	1443	489	19.89	1475	237	4.41	0.0186	41460	0.383
6/21/78	663082 JT9D-3A	JET A	Idle	1.02	57	371	1065	725	655	3.57	370	52	0.52	0.0100	3192	0.586
			Approach	1.08	57	601	1470	945	727	8.44	700	114	1.39	0.0123	13107	0.382
			Cruise	1.19	57	744	1830	1157	796	13.58	1060	175	2.53	0.0145	25752	0.354
			Climbout	1.32	57	834	2065	1334	905	17.48	1360	217	3.63	0.0167	35965	0.363
			Takeoff	1.42	58	885	2260	1453	981	19.95	1505	241	4.47	0.0185	42815	0.376
6/22/78	662794 JT9D-3A	JET A	Idle	1.01	59	375	1068	729	653	3.60	350	49	0.49	0.0100	2582	0.683
			Approach	1.07	59	620	1460	907	712	8.70	675	110	1.35	0.0123	12317	0.395
			Cruise	1.18	58	761	1785	1117	786	13.50	1030	170	2.45	0.0145	24534	0.360
			Climbout	1.32	58	848	2070	1305	905	17.72	1352	215	3.69	0.0172	35870	0.370
			Takeoff	1.41	58	903	2270	1413	970	20.44	1485	239	4.49	0.0188	42239	0.383

Table 14

TF30-P-1 PARTICULATE EMISSION CHARACTERIZATION DATA

Date	Power Setting	Sample Information			Mass Emissions		Particle Size by
		Weight, mg	Flow cfm	Time, Min.	kg/hr*	g/kg fuel	Microscopy, dg, μm
6/8/77	Idle	10.0	1.39	15	1.80	4.41	
	Approach	14.7	2.18	7	7.00	6.57	
	Cruise	20.2	2.58	5	15.6	7.26	
	Climbout	11.6	2.77	3	15.3	5.63	
	Takeoff	10.8	2.77	2	22.0	7.06	
6/9/77	Cruise	14.1	2.58	4	13.6	6.34	0.063
	Cruise	14.5	2.58	4	14.0	6.57	0.072
	Cruise	14.2	2.58	4	13.8	6.42	0.071
	Cruise	14.1	2.58	4	13.6	6.39	0.075
6/10/77	Idle	4.2	1.39	15	0.76	1.85	0.046
	Approach	9.7	2.18	5	6.4	5.94	0.063
	Cruise	16.1	2.58	4	15.6	7.27	0.047
	Climbout	12.4	2.78	3	16.3	6.00	0.050
	Takeoff	10.2	2.78	2	20.9	6.74	0.060

* Based on total air--primary plus fan, W_{at}

Table 15

JT8D PARTICULATE EMISSION CHARACTERIZATION DATA

Date	Engine No. & Type	Fuel Type	Power Setting	Sample Information: Weight, mg	Sample Information: Flow, cfm	Sample Information: Time, min.	Mass Emissions: kg/hr*	Mass Emissions: g/kg fuel	Particle Size by microscopy: dg	Particle Size by microscopy: σ_g	EAA Particle Conc. Data: $10^7 N_t$/cc	EAA Particle Conc. Data: $V_t 10^3 \mu m^3$/cc
1/9/78	654957	JET A	Idle	1.7	1.4	15	0.40	0.79	0.052	1.7		
	JT8D-7		Approach	3.0	2.2	5	2.56	2.37	0.086	1.7		
			Cruise	3.3	2.6	4	4.11	2.02	0.081	1.7		
			Climbout	3.6	2.8	3	6.45	2.15	0.096	1.6		
			Takeoff	0.7	2.8	2	2.00	0.56	0.099	1.7		
4/24/78	648796	JET A	Idle	---	---	--	--	--	0.042	1.7		
	JT8D-15		Approach	3.6	2.2	20	0.74	0.67	0.067	1.8		
			Cruise	4.8	2.6	10	2.35	1.09	0.092	1.8		
			Climbout	11.3	2.8	6	9.84	3.23	0.088	1.9		
			Takeoff	---	---	--	--	--	0.097	2.0		
4/25/78	648796	PK	Idle	---	---	--	--	--	0.032	1.7		
	JT8D-15		Approach	1.0	2.2	20	0.21	0.18	0.037	1.8		
			Cruise	1.1	2.6	10	0.52	0.23	0.079	1.9		
			Climbout	3.1	2.8	6	2.70	0.88	0.075	1.8		
			Takeoff	3.9	2.8	6	3.54	0.96	0.077	1.9		
4/25/78	648735	JET A	Idle	---	---	--	--	--	0.043	1.6		
	JT8D-7		Approach	4.0	2.2	20	0.85	0.77	0.054	2.1		
			Cruise	1.2	2.6	10	0.60	0.29	0.069	2.0		
			Climbout	0.6	2.8	6	0.54	0.18	0.049	2.3		
			Takeoff	1.7	2.8	6	1.60	0.44	0.060	2.2		
6/20/78	696572	JET A	Idle	---	---	--	--	--	0.042	1.7	9.30	0.52
	JT8D-15		Approach	2.9	2.2	20	0.60	0.53	0.064	1.7	2.10	2.74
			Cruise	4.4	2.6	10	2.15	1.01	0.072	1.6	2.27	6.39
			Climbout	1.8	2.8	6	1.57	0.52	0.076	1.6	2.64	7.29
			Takeoff	3.0	2.8	6	2.81	0.77	0.076	1.6	1.90	5.42

* Based on total air -- primary plus fan, W_{at}

Table 16

JT9D PARTICULATE EMISSION CHARACTERIZATION DATA

Date	Engine No. & Type	Fuel Type	Power Setting	Sample Information: Weight, mg	Sample Information: Flow, cfm	Sample Information: Time, min.	Mass Emissions: kg/hr*	Mass Emissions: g/kg fuel	Particle Size by microscopy: dg	Particle Size by microscopy: σ_g	EAA Particle Conc. Data: $10^6 N_t$/cc	EAA Particle Conc. Data: $V_t 10^2 \mu m^3$/cc
1/9/78	662734	JET A	Climbout	---	--	--	--	--	0.084	1.6	----	---
	JT9D-3A		Takeoff	---	--	--	--	--	0.117	1.6	----	---
4/20/78	663031	JET A	Approach	1.4	0.81	20	0.49	0.20	0.054	1.8	66.7	6.05
	JT9D-3A		Cruise	---	--	--	--	--	---	---	60.6	4.72
			Climbout	---	--	--	--	--	---	---	114.0	4.93
			Takeoff	6.1	2.2	12	2.80	0.38	0.077	1.8	3.73	7.57
4/21/78	663031	PK	Approach	3.1	0.81	20	1.10	0.46	0.054	1.6	3.67	0.78
	JT9D-3A		Cruise	---	--	--	--	--	---	---	1.93	1.52
			Climbout	---	--	--	--	--	---	---	2.81	2.89
			Takeoff	---	--	--	--	--	0.050	1.9	6.00	6.29
6/21/78	663082	JET A	Idle	---	--	--	--	--	0.043	1.6	23.4	0.60
	JT9D-3A		Approach	---	--	--	--	--	0.048	1.7	6.11	10.6
			Cruise	1.1	1.2	25	0.33	0.079	---	---	4.54	5.27
			Climbout	---	--	--	--	--	0.043	1.9	7.21	4.96
			Takeoff	---	--	--	--	--	---	---	96.6	11.7
6/22/78	662794	JET A	Idle	---	--	--	--	--	---	---	0.33	0.48
	JT9D-3A		Approach	---	--	--	--	--	---	---	1.03	4.18
			Cruise	---	--	--	--	--	0.042	1.7	48.9	3.83
			Climbout	1.4	1.6	30	0.32	0.052	0.045	1.6	3.31	2.24
			Takeoff	---	--	--	--	--	---	---	5.45	2.05

* Based on primary air, W_{ap}

Primary air is that air associated with the combustion process. With the JT9D engine, the sampling rake assembly was placed directly behind the exit nozzle and sampled only the "core" or primary air flow. Use of primary air flow for the JT9D engine is supported by the work at Pratt and Whitney[8] where the FAA diamond rake was compared to the P & W cruciform (equal area) sampling rake. With the mixed flow engines, the sampling rake was located where the fan air and primary air have already mixed. As a result, the sampler is not sampling primary air alone as with the JT9D engine. This problem was addressed during Phase I of the project. With the exit plane mappings available for the gaseous emissions the FAA diamond rake was shown to extract a representative sample of the total engine flow.

Emissions, as a function of fuel burned, were calculated by the formula:

$$\text{Emission rate, g/kg fuel} = 0.6124 \, \frac{\text{Emission rate, kg/hr}}{\text{Fuel Consumed, lbs/sec}}$$

Particle sizes reported in Tables 14, 15, and 16 are based on the diameter of a circle of area equal the area of the particle as determined by the Quantimet-720 image analyzer from electron photomicrographs. The individual particle diameters were plotted on log-probability paper and the geometric mean diameter, d_g, and the geometric standard deviation, σ_g, of the particle size distributions extracted from the plots. A typical plot is shown in Figure 7. Size distributions can be reconstructed from d_g and σ_g, if desired.

Data obtained with the Electrical Aerosol Analyzer (EAA) during the June 1978 JT8D and JT9D engine tests are plotted in Figures 8 through 17. The EAA is a real-time aerosol size analyzer designed to measure the size distribution of particles in the 0.0032 to 1 μm diameter range.[(12)] The measurement is performed by first exposing the aerosol to unipolar gaseous ions in a diffusion charger and then measuring the aerosol mobility with the mobility analyzer. The size distribution is then derived from the measured mobility distribution. Number, surface area, and volume distribu-

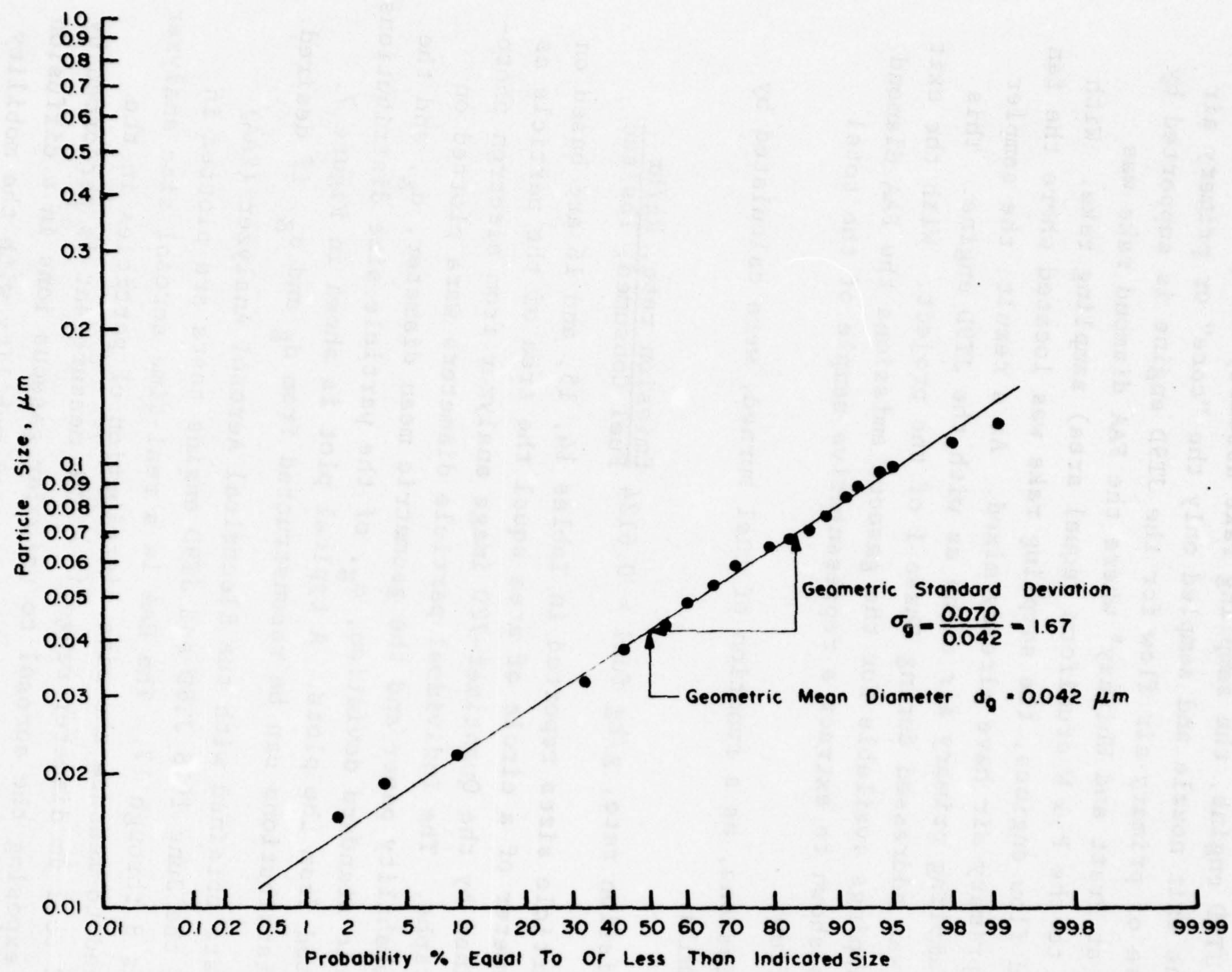


FIG. 7 PARTICLE SIZE DISTRIBUTION OF EMISSIONS FOR JT9D-3A ENGINE 662794 CRUISE POWER JET A FUEL

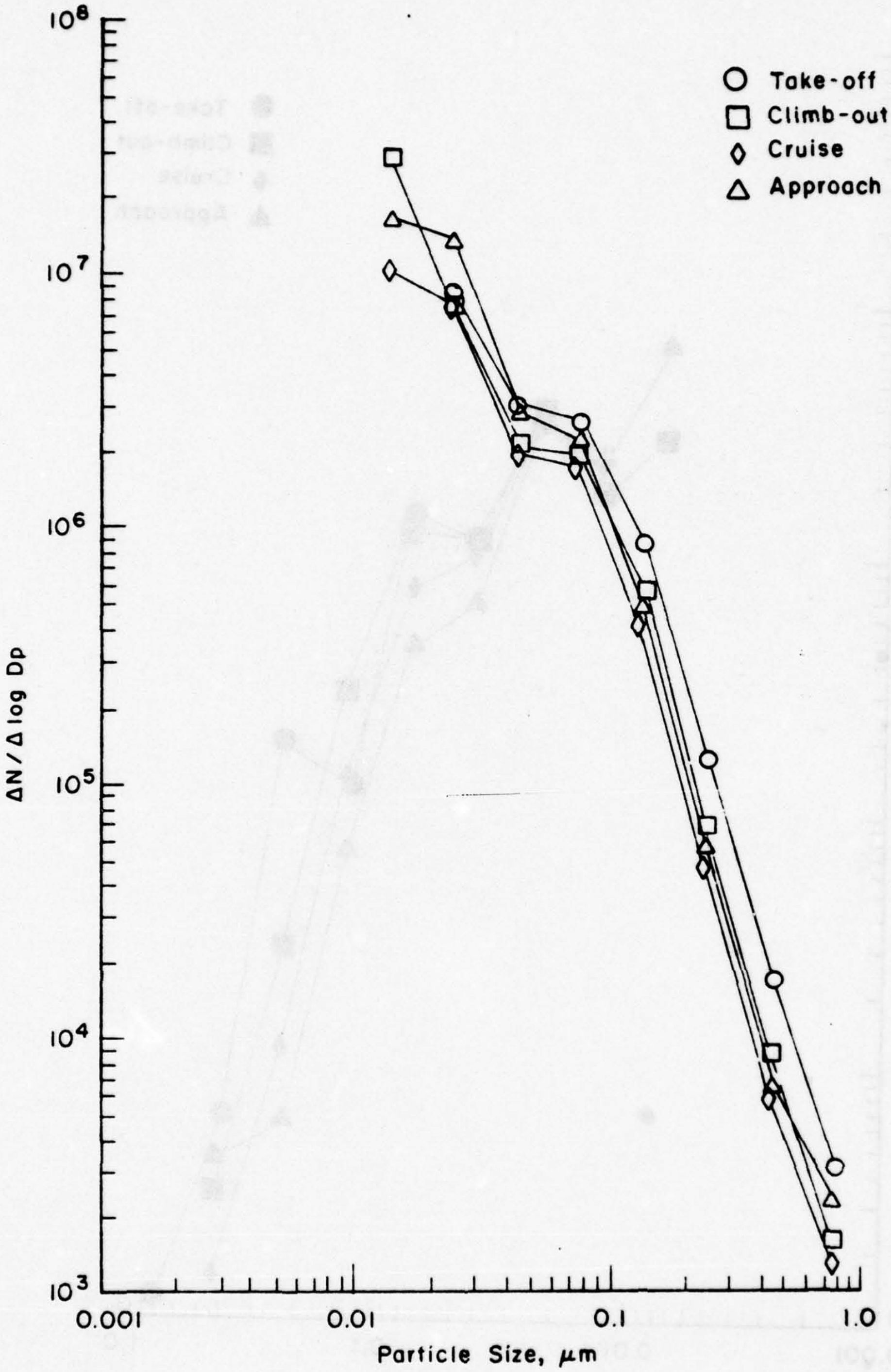


Fig. 8 EAA AEROSOL SIZE DISTRIBUTION BY NUMBER JT9D ENGINE 663031 JET A FUEL

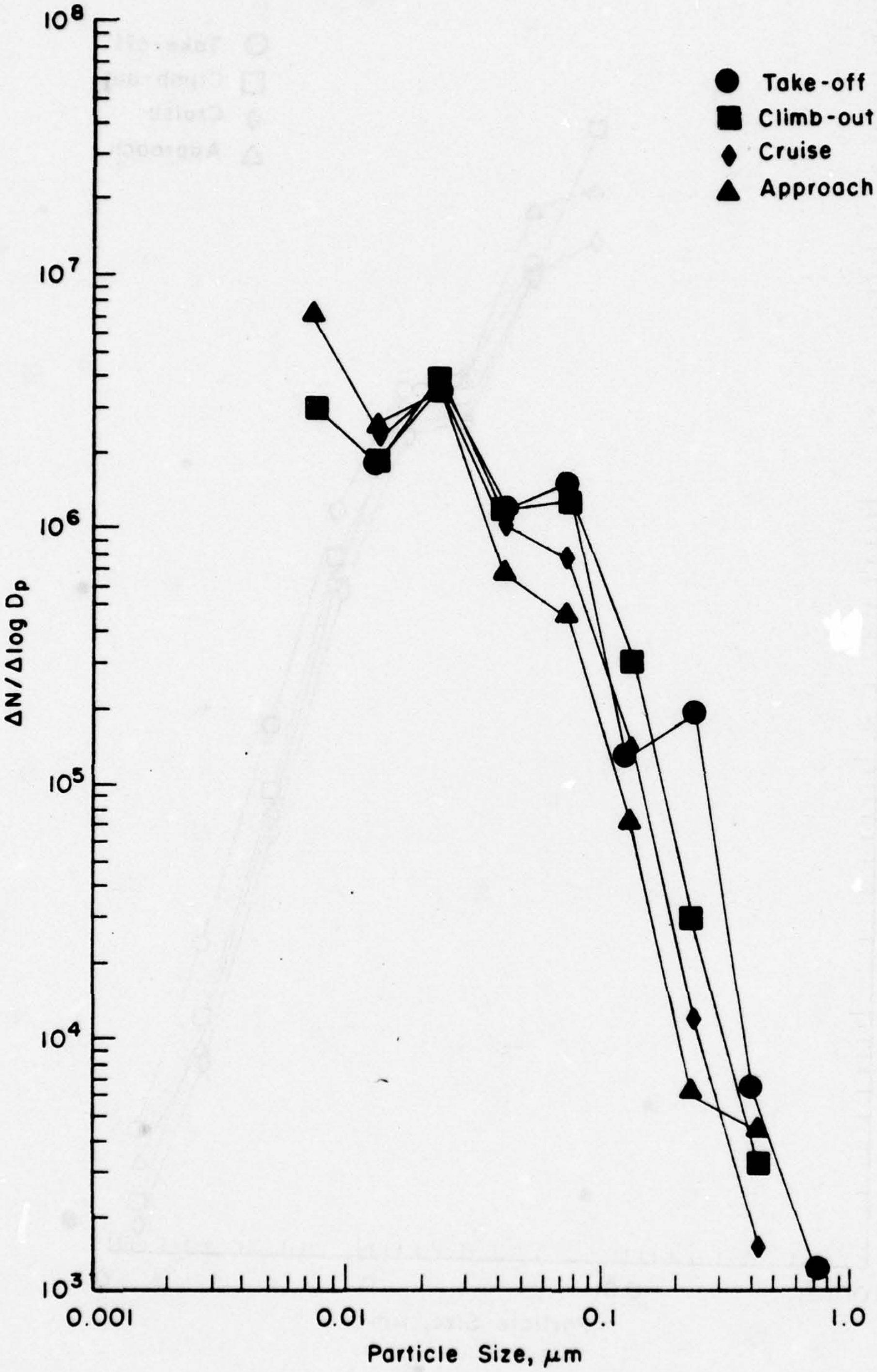


Fig. 9 EAA AEROSOL SIZE DISTRIBUTION BY NUMBER JT9D ENGINE 663031 PK FUEL

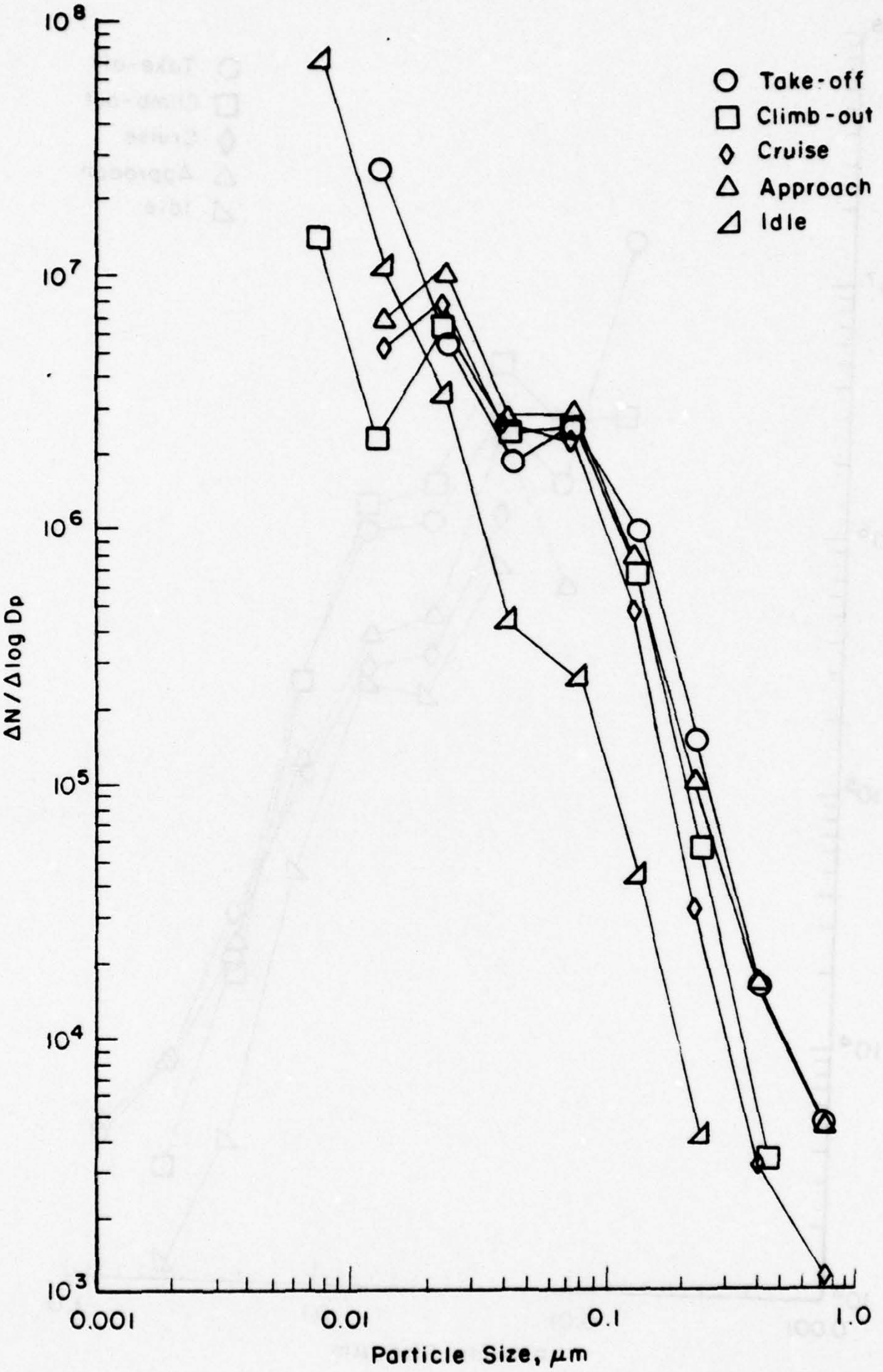


Fig. 10 EAA AEROSOL SIZE DISTRIBUTION BY NUMBER JT9D ENGINE 663082 JET A FUEL

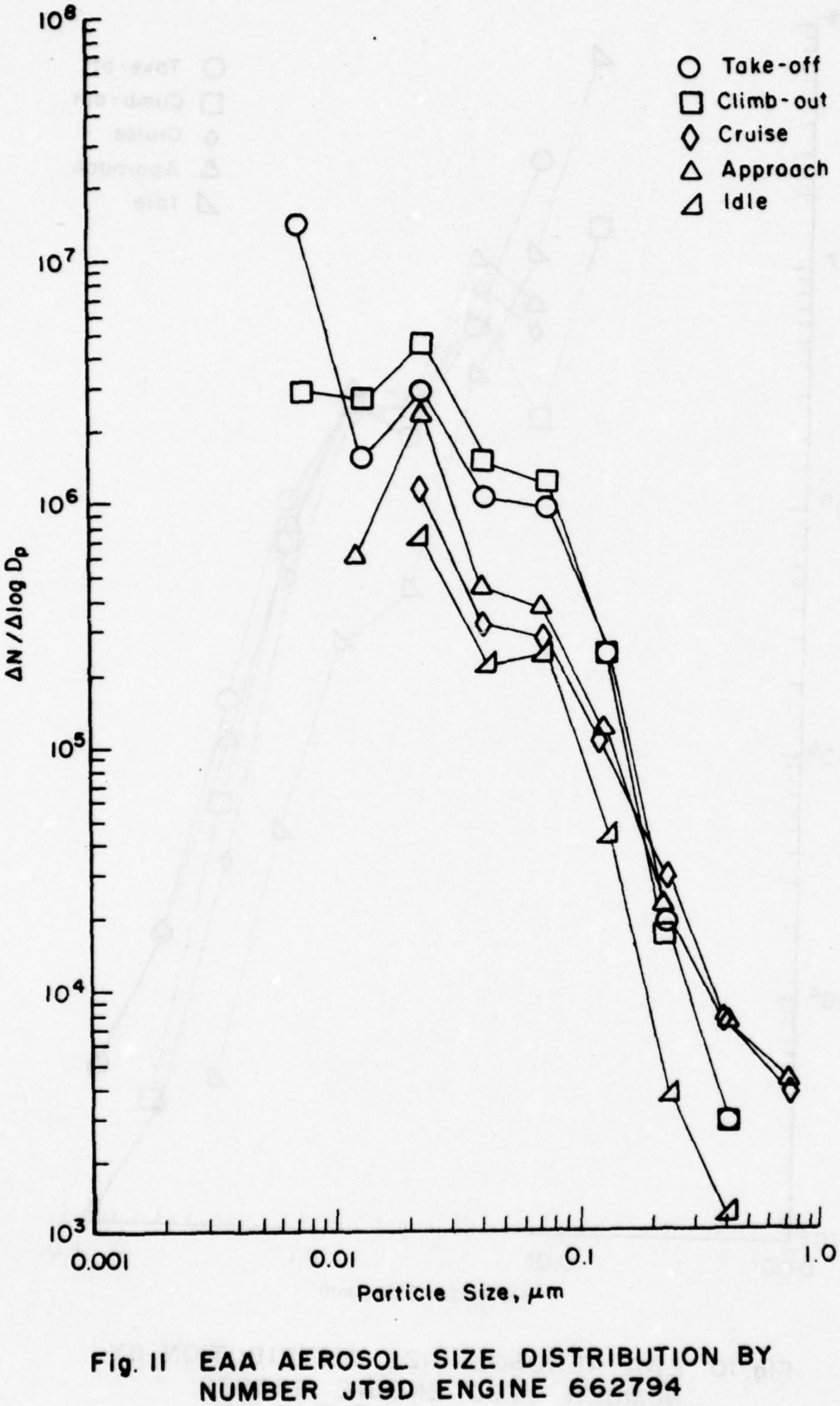


Fig. II EAA AEROSOL SIZE DISTRIBUTION BY NUMBER JT9D ENGINE 662794 JET A FUEL

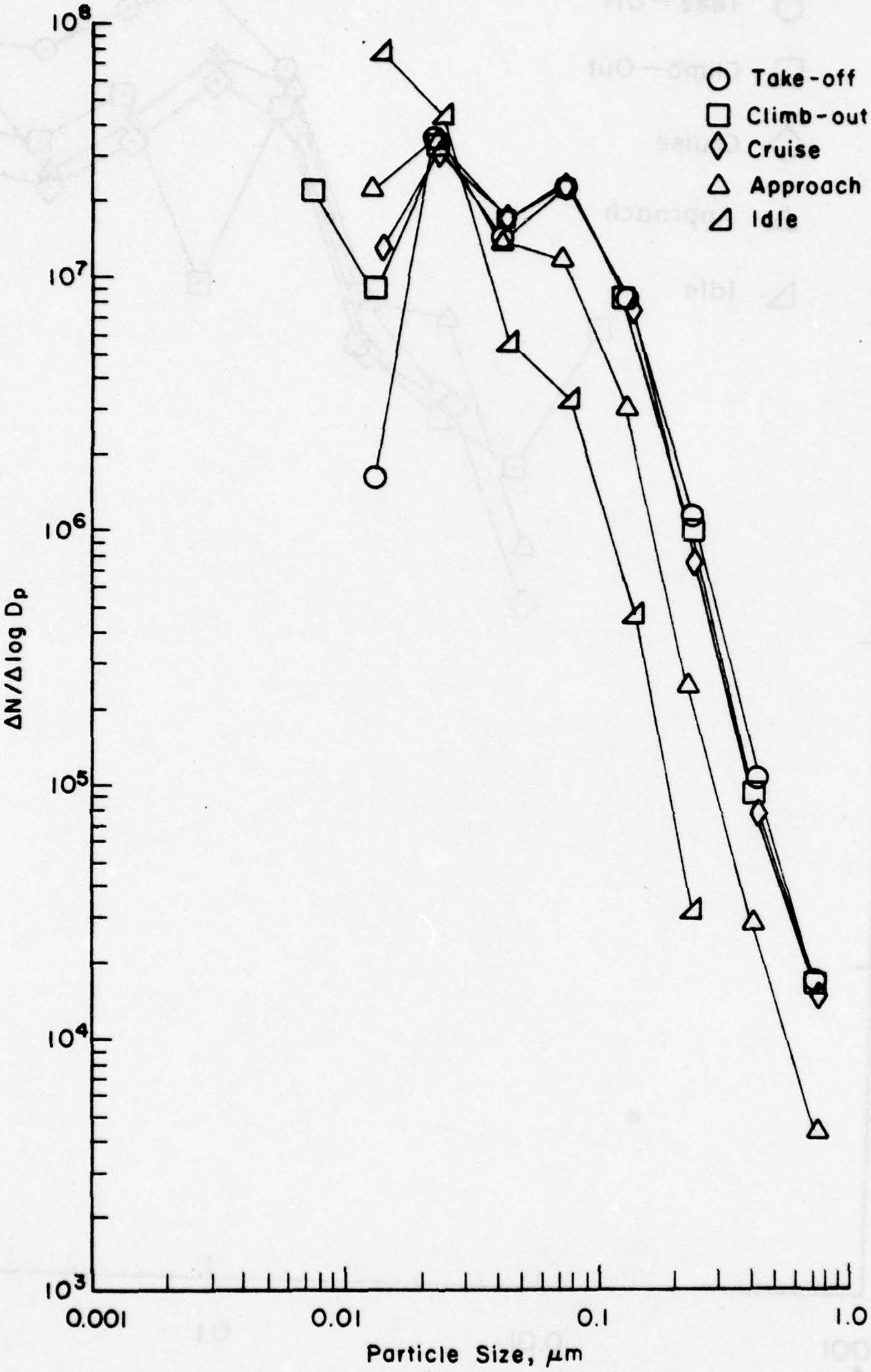


Fig. 12 EAA AEROSOL SIZE DISTRIBUTION BY NUMBER JT8D-15 ENGINE 696572 JET A FUEL

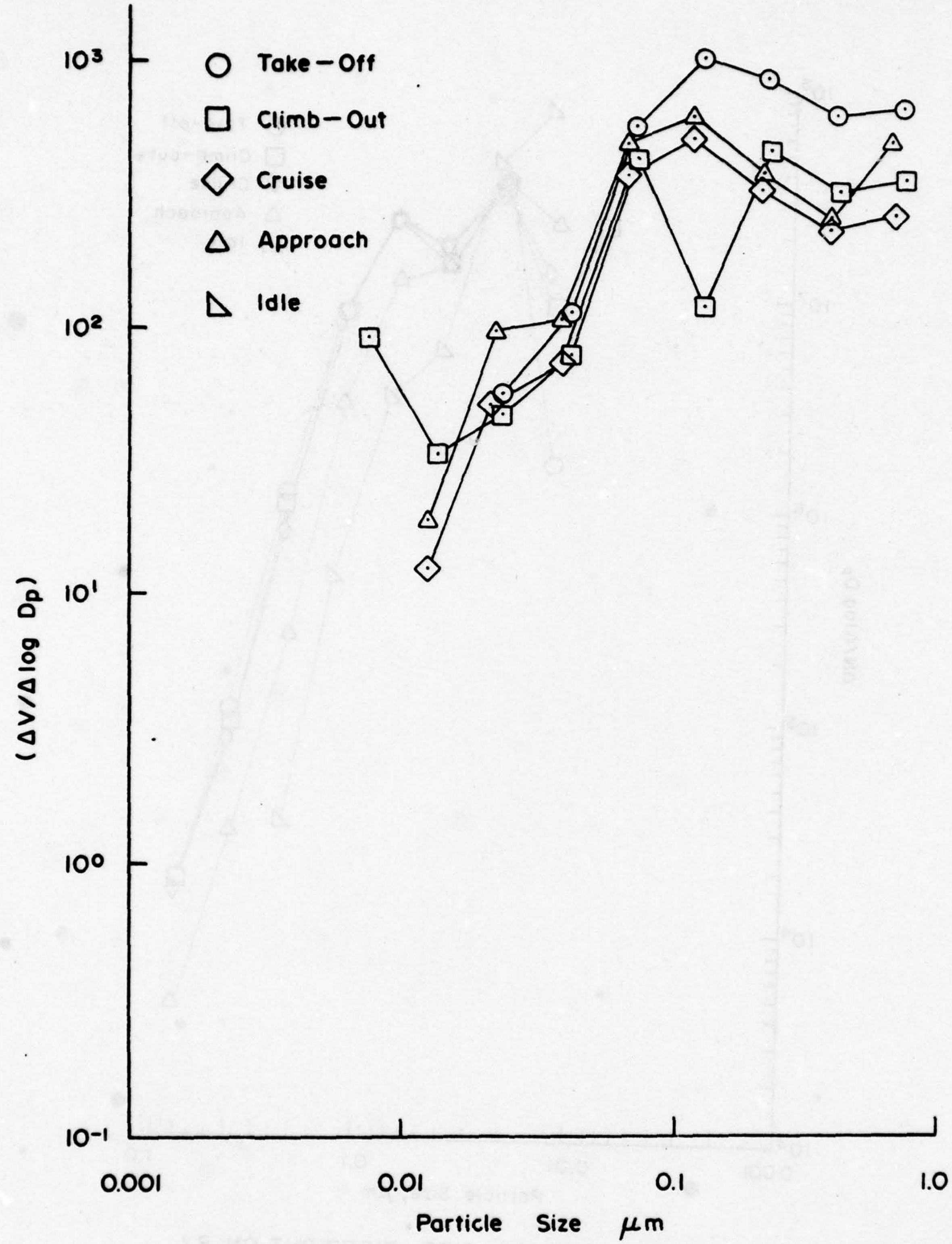


FIG. 13 EAA AEROSOL SIZE DISTRIBUTION BY VOLUME
JT9D ENGINE 663031 JET A FUEL

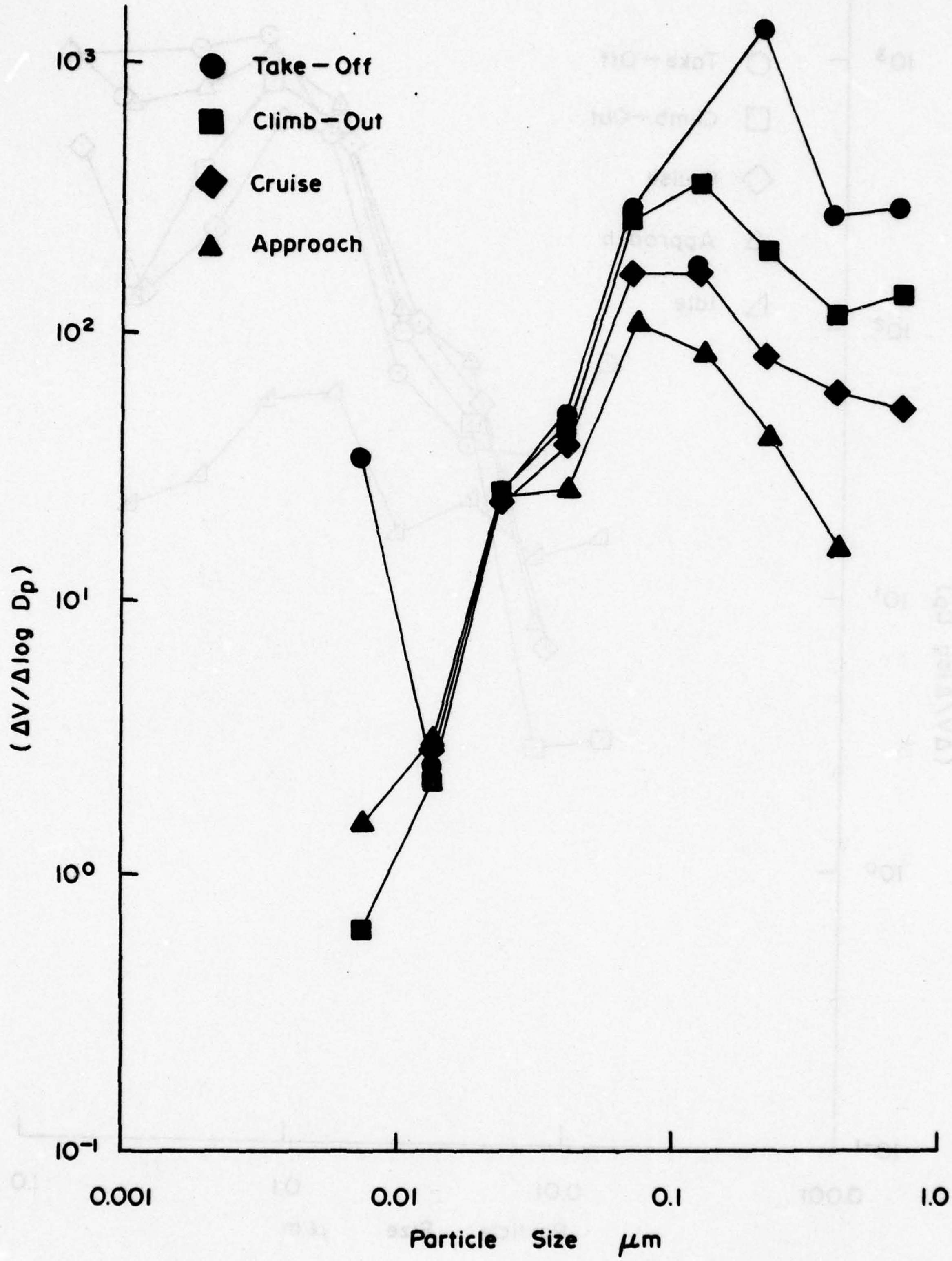


FIG. 14 EAA AEROSOL SIZE DISTRIBUTION BY VOLUME
JT9D ENGINE 663031 PK FUEL

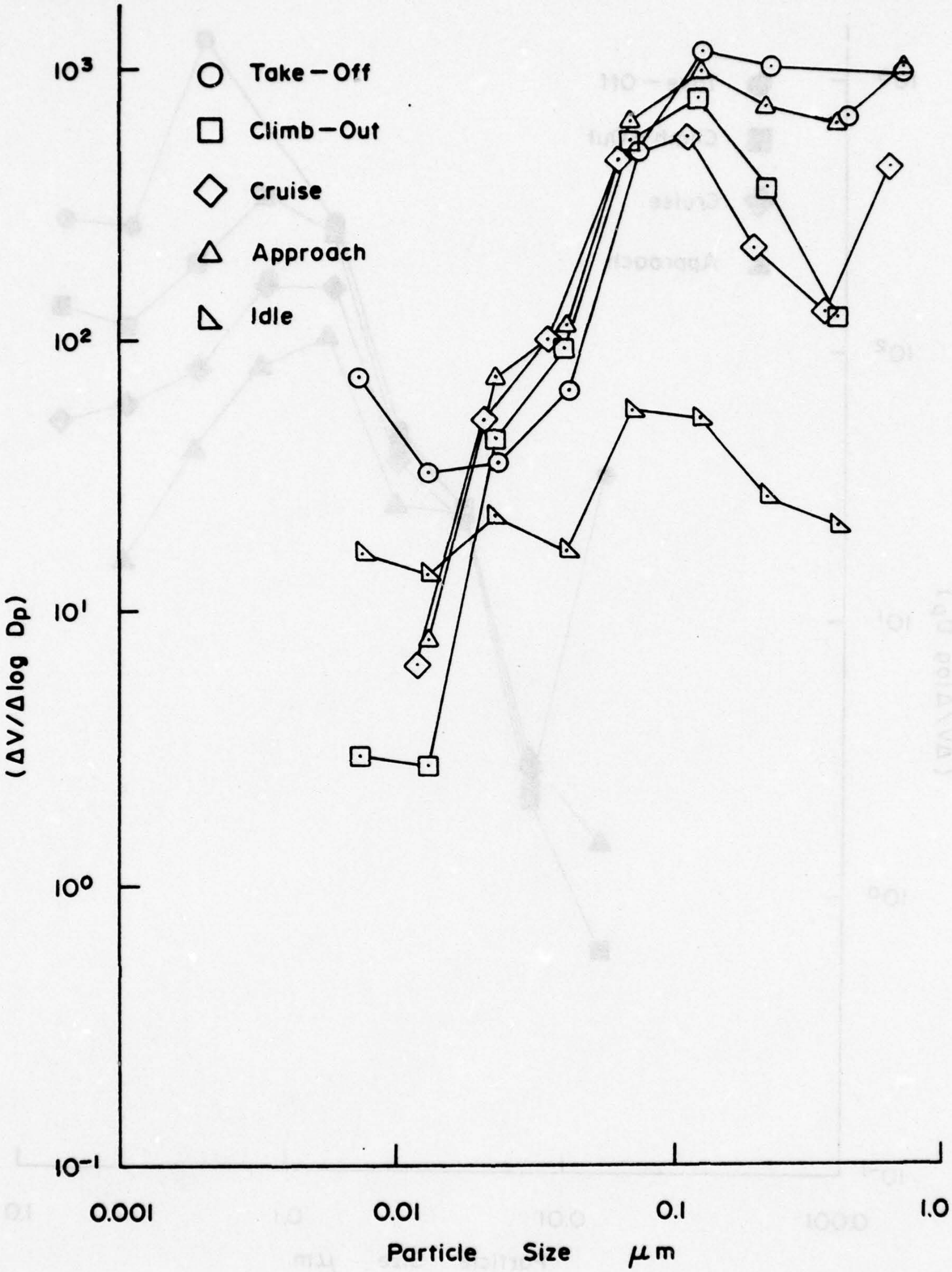


FIG. 15 EAA AEROSOL SIZE DISTRIBUTION BY VOLUME JT9D ENGINE 663082 JET A FUEL

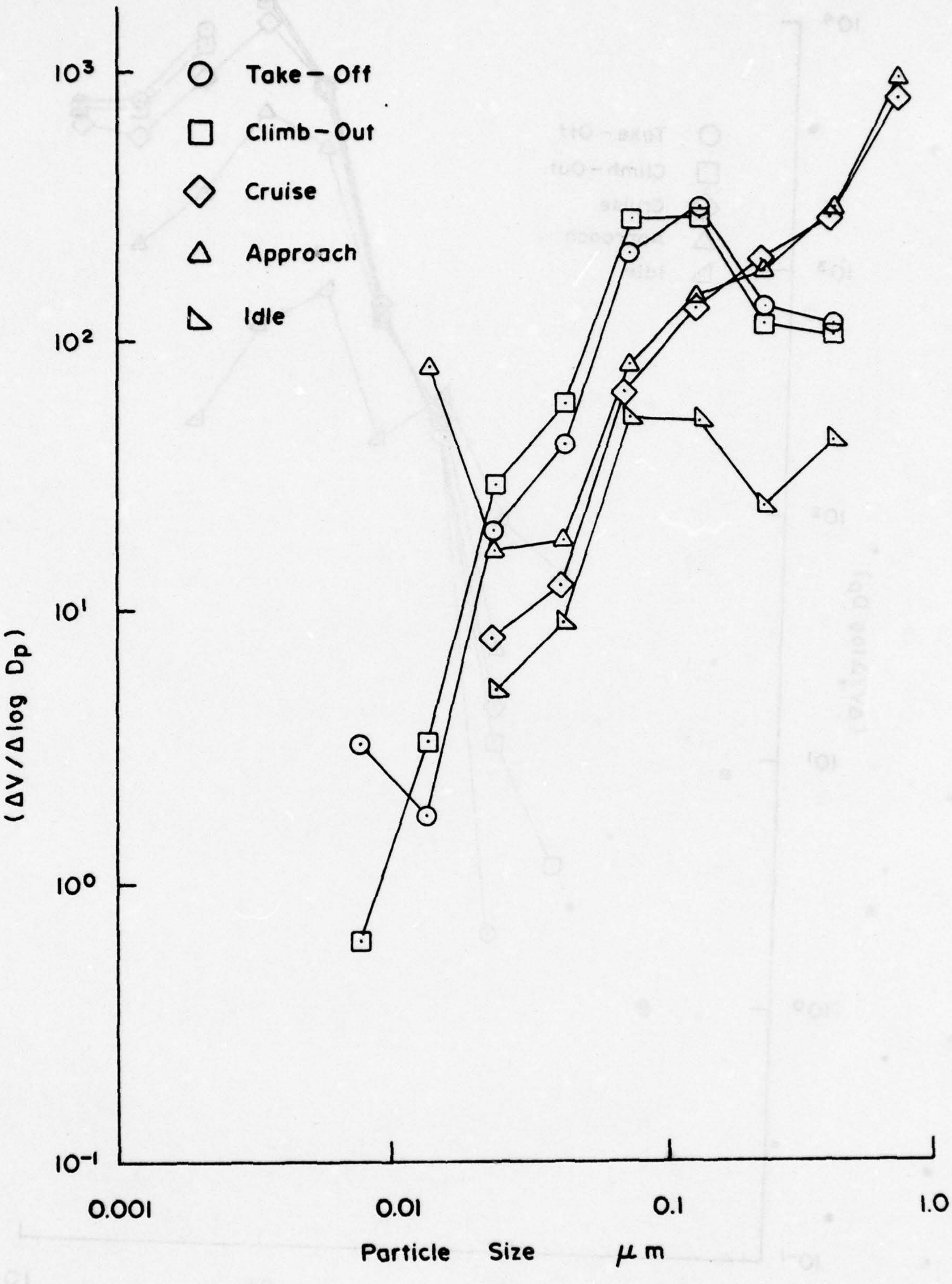


FIG. 16 EAA AEROSOL SIZE DISTRIBUTION BY VOLUME JT9D ENGINE 662794 JET A FUEL

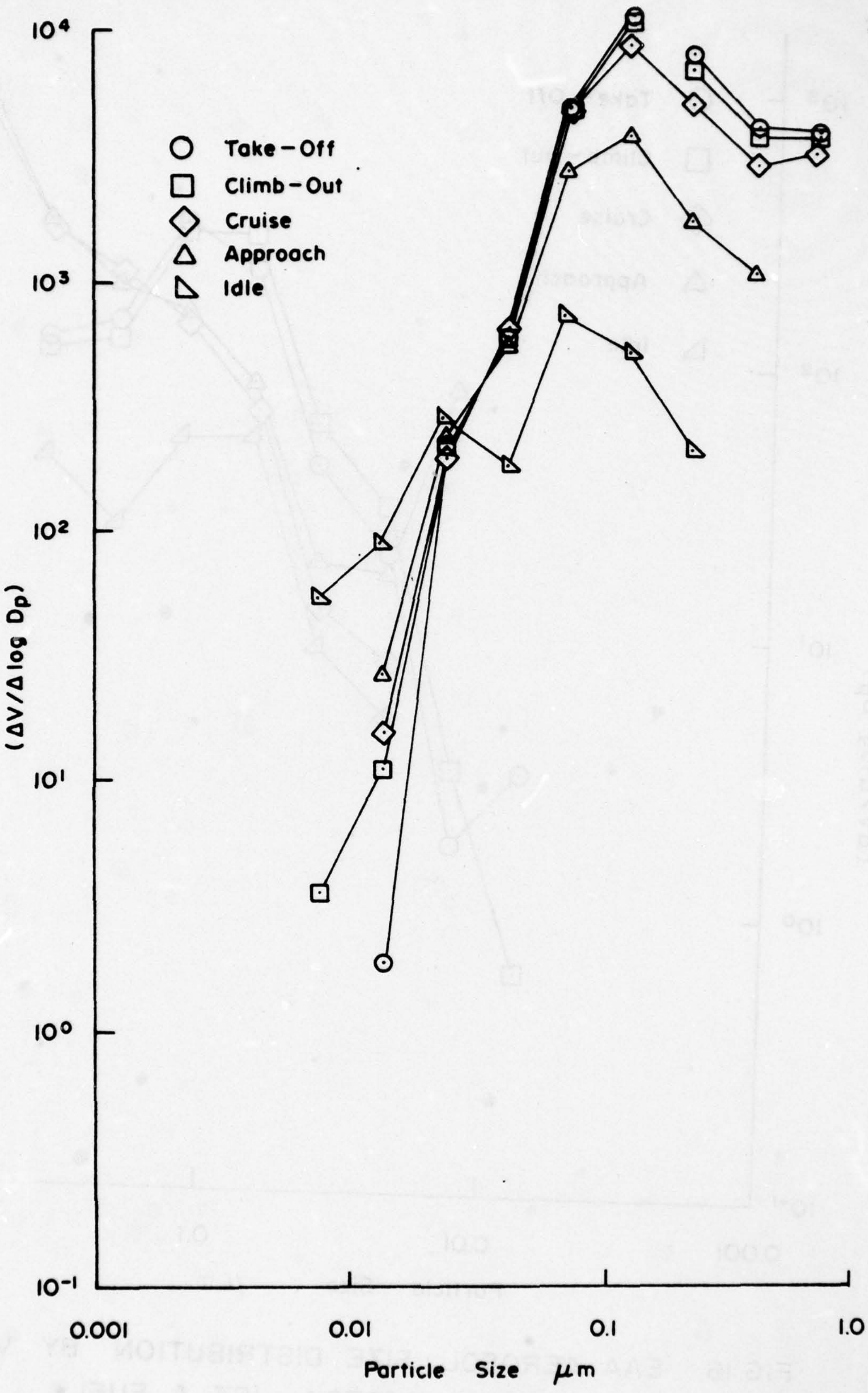


FIG. 17 EAA AEROSOL SIZE DISTRIBUTION BY VOLUME
JT8D-15 ENGINE 696572 JET A FUEL

tion can be derived. In this study only the number and volume distributions are reported.

Particle shape data are presented in Figures 18 through 25. The particle shape parameter, area/perimeter^2, is plotted as a function of the particle diameter of a circle of area equivalent to the area of the exhaust particle.

4.2 Discussion

4.2.1 Engines Performance Variability

The three engines tested represent different eras in performance requirements and the implementation of emission controls through engine design and combustion technology. The performance differences are illustrated in Figures 26, 27, and 28. Figure 26 plots engine thrust as a function of fuel flow. Note that the JT8D engine provides slightly more thrust at power settings above approach than the TF-30 engine per units of fuel usage while the JT9D engine provides significantly more thrust than either the JT8D or TF-30 at power settings above idle. Figure 27 shows the fuel/primary air ratios of the engines as a function of fuel flow. Above idle the TF-30 operates at relatively high fuel/air ratios. The lean burning character of the JT9D is illustrated. In a similar manner, the thrust specific fuel consumption (TSFC) is lowest for the JT9D engine, Figure 28. The performance variation within an engine type is small as demonstrated by the data.

4.2.2 Mass Emission Rate

The particulate mass emission rates, kg/hr, for the TF-30, JT8D, and JT9D engines are plotted in Figure 29 as a function of fuel flow and in Figure 30 as a function of thrust. Due to the variability in the JT8D and JT9D results, data envelopes are presented for these engines. Significant is that these engines generate separate envelopes. Noteworthy is the significant improvement in emissions with engine technology. This improvement is illustrated amply in Table 17 where the average mass emission rates are given as a function of power setting.

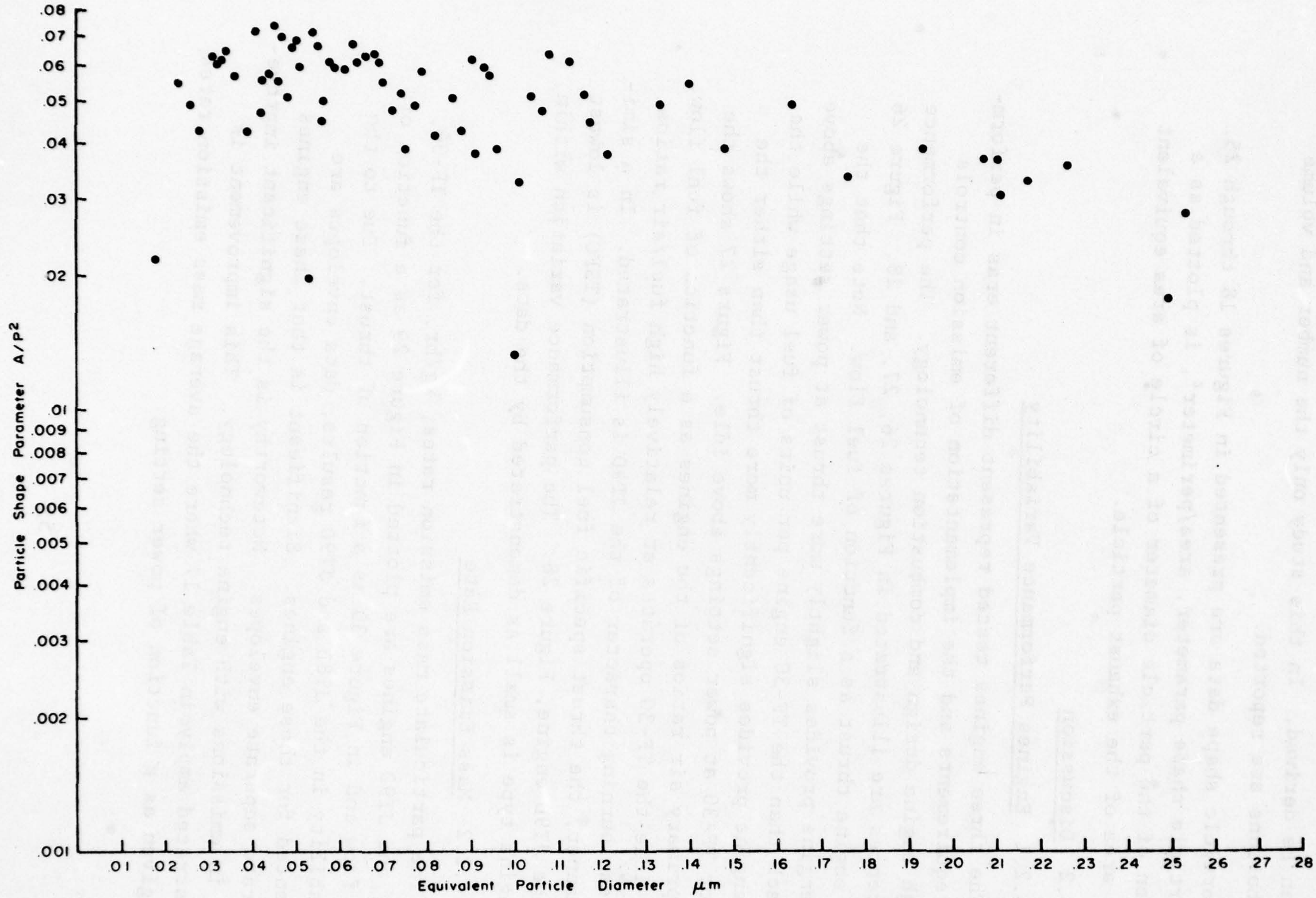


FIG. 18a PARTICLE SHAPE JT8D-15 ENGINE 648796 JET A FUEL APPROACH POWER

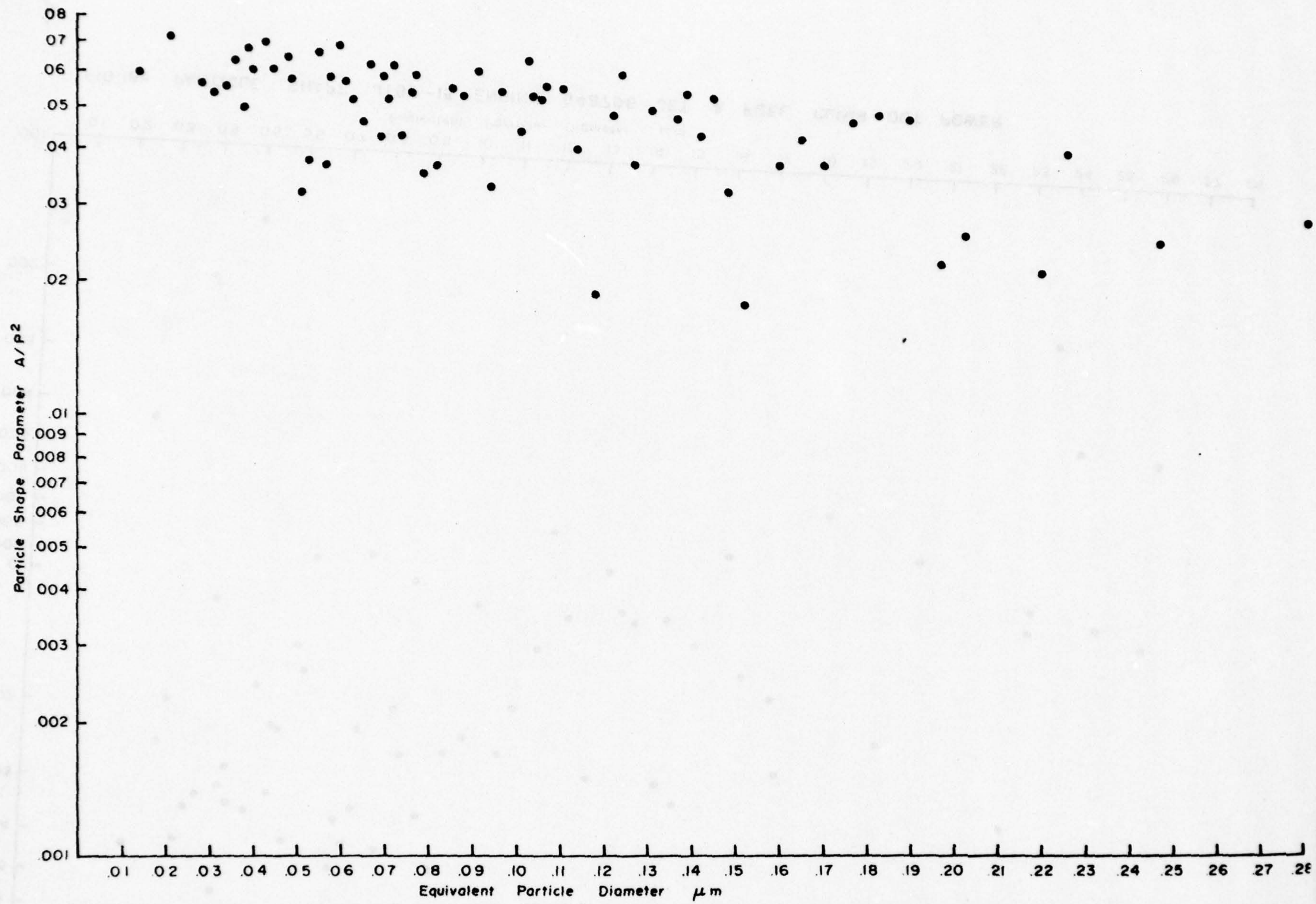


FIG. 18b PARTICLE SHAPE JT8D-15 ENGINE 648796 JET A FUEL CRUISE POWER

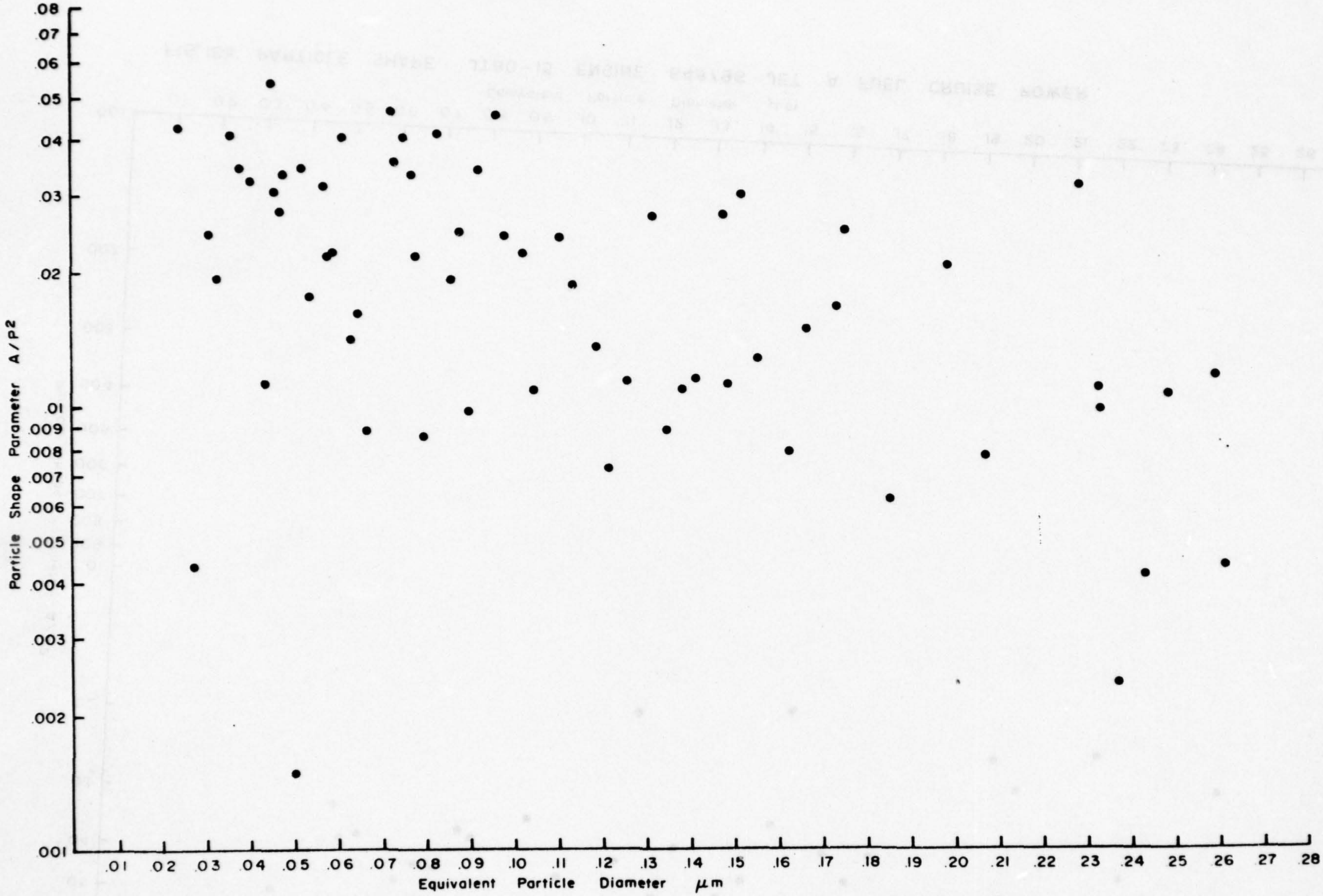


FIG. 18c PARTICLE SHAPE JT8D-15 ENGINE 648796 JET A FUEL CLIMB OUT POWER

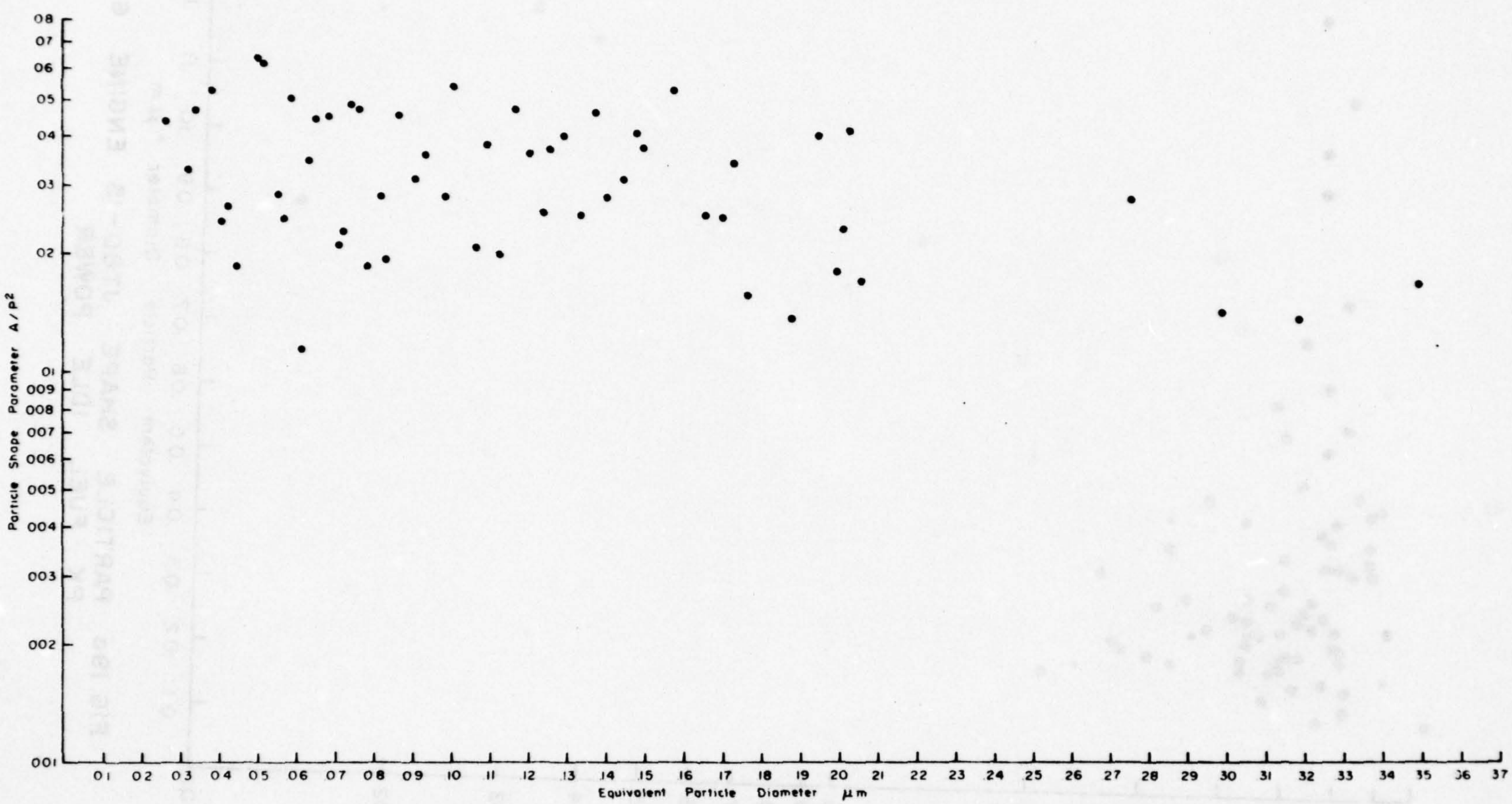


FIG. 18d PARTICLE SHAPE JT8D-15 ENGINE 648796 JET A FUEL TAKEOFF POWER

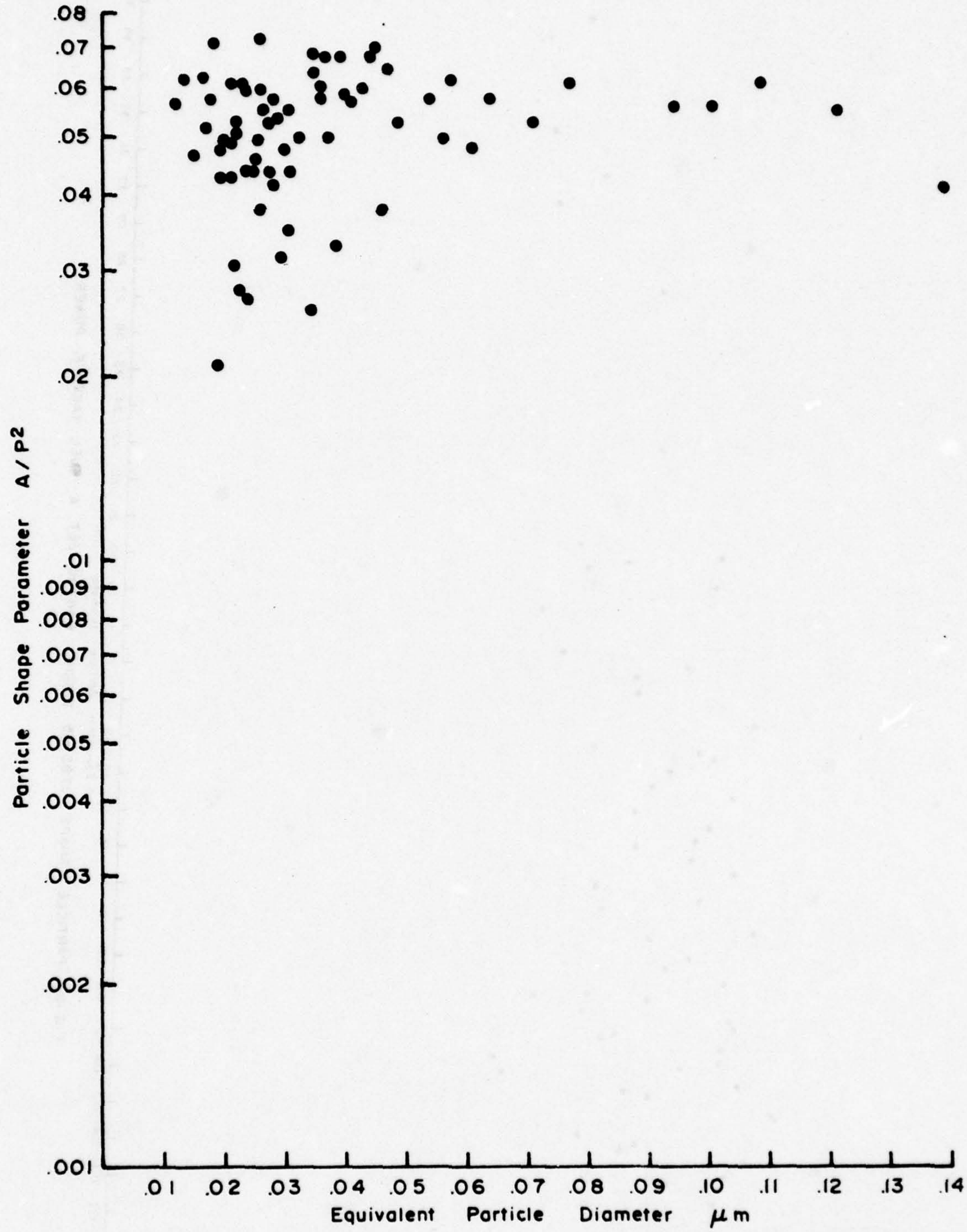


FIG. 19a PARTICLE SHAPE JT8D-15 ENGINE 648796
PK FUEL IDLE POWER

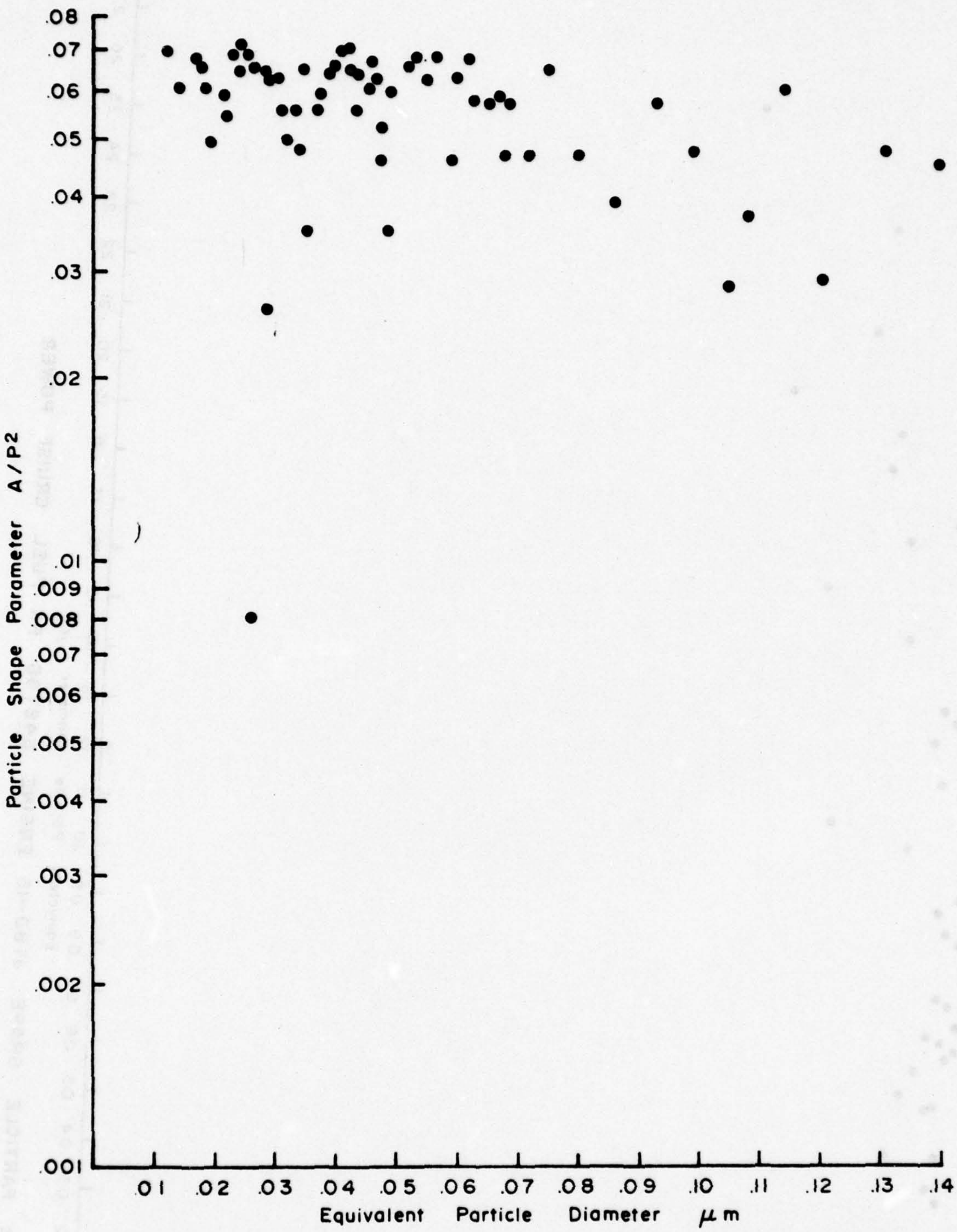


FIG. 19b PARTICLE SHAPE JT8D-15 ENGINE 648796
PK FUEL APPROACH POWER

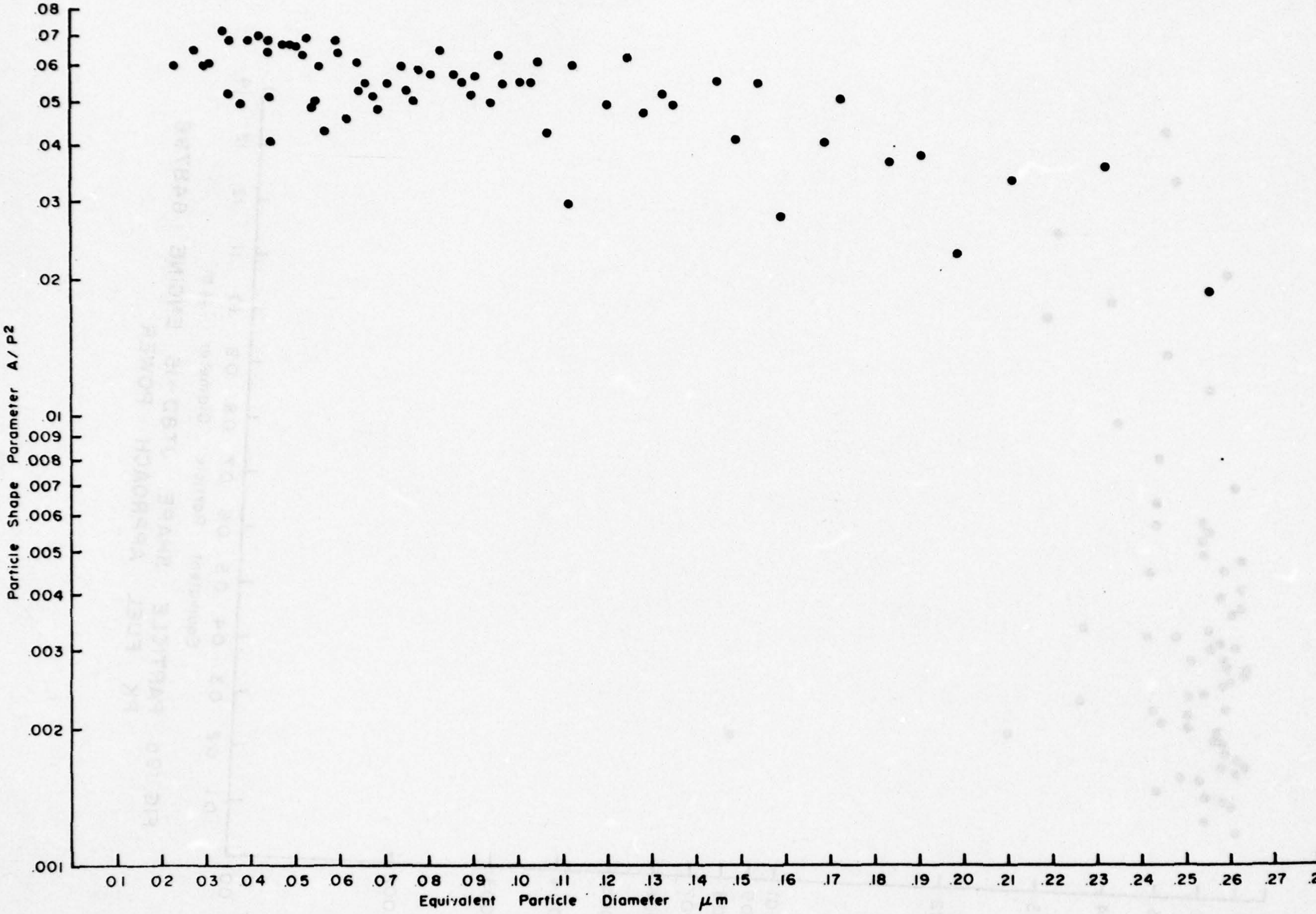


FIG 19c PARTICLE SHAPE JT8D-15 ENGINE 648796 PK FUEL CRUISE POWER

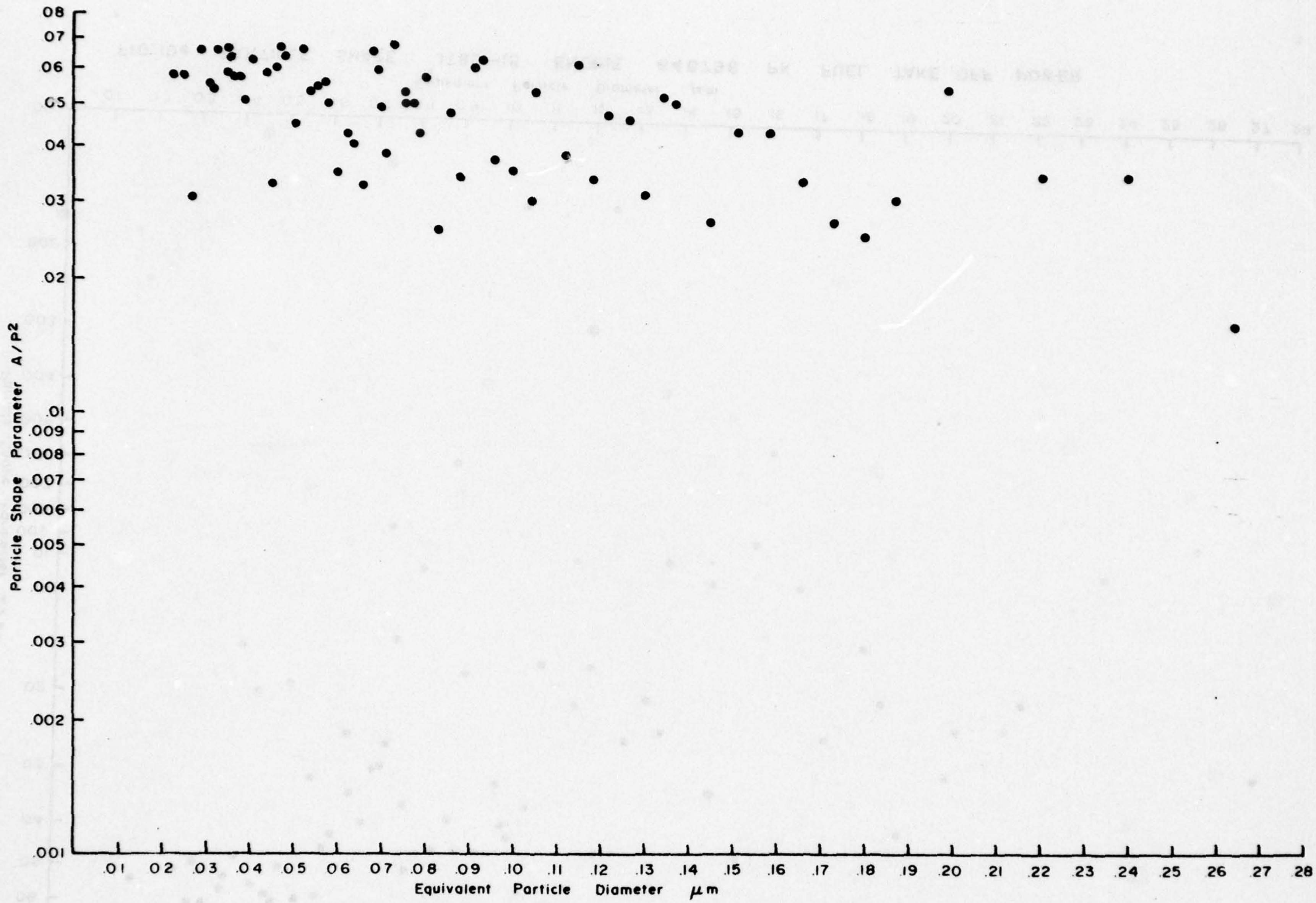


FIG. 19d PARTICLE SHAPE JT8D-15 ENGINE 648796 PK FUEL CLIMB OUT POWER

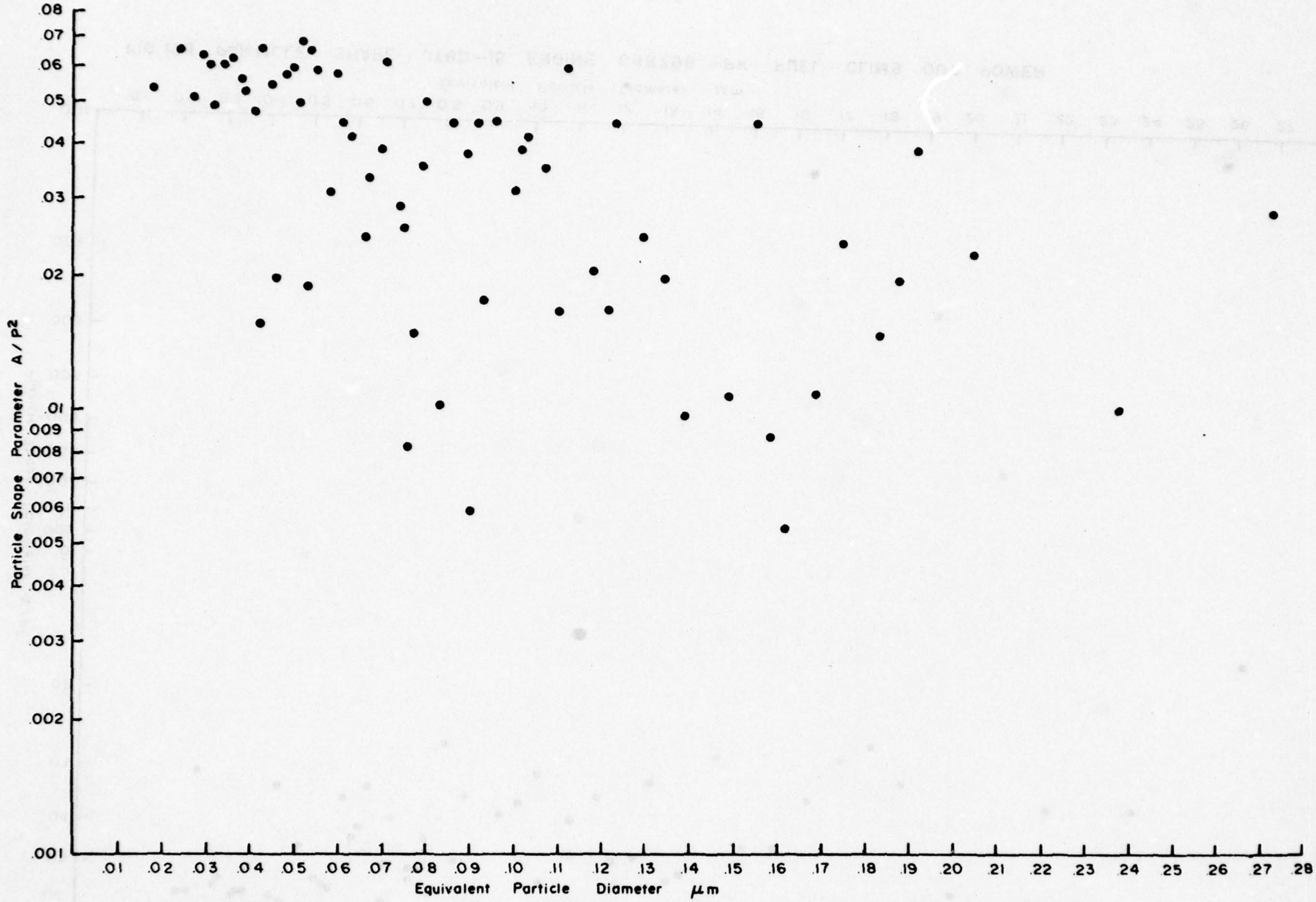


FIG. 19e PARTICLE SHAPE JT8D-15 ENGINE 648796 PK FUEL TAKE OFF POWER

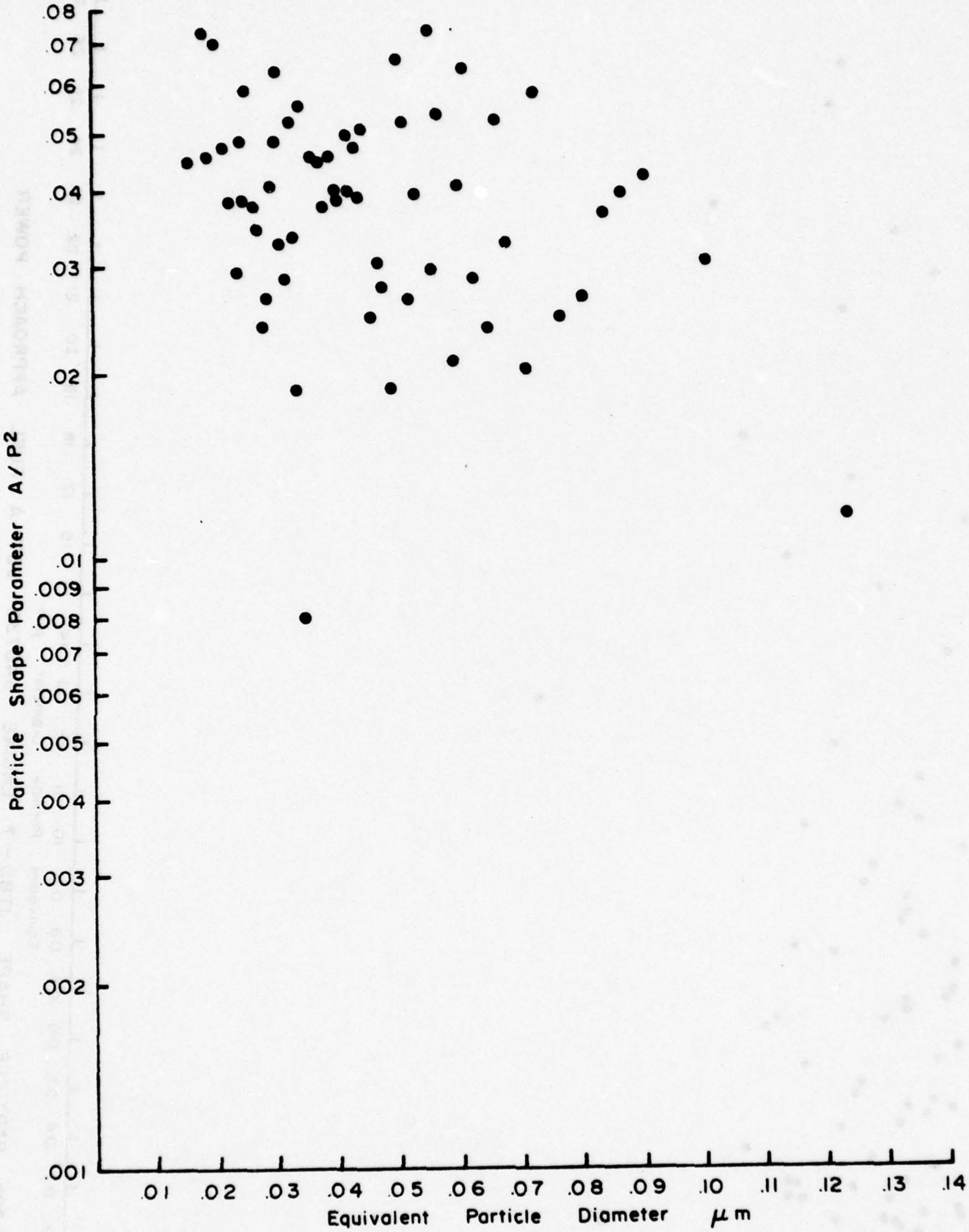


FIG.20a PARTICLE SHAPE JT8D-7 ENGINE 648735
JET A FUEL IDLE POWER

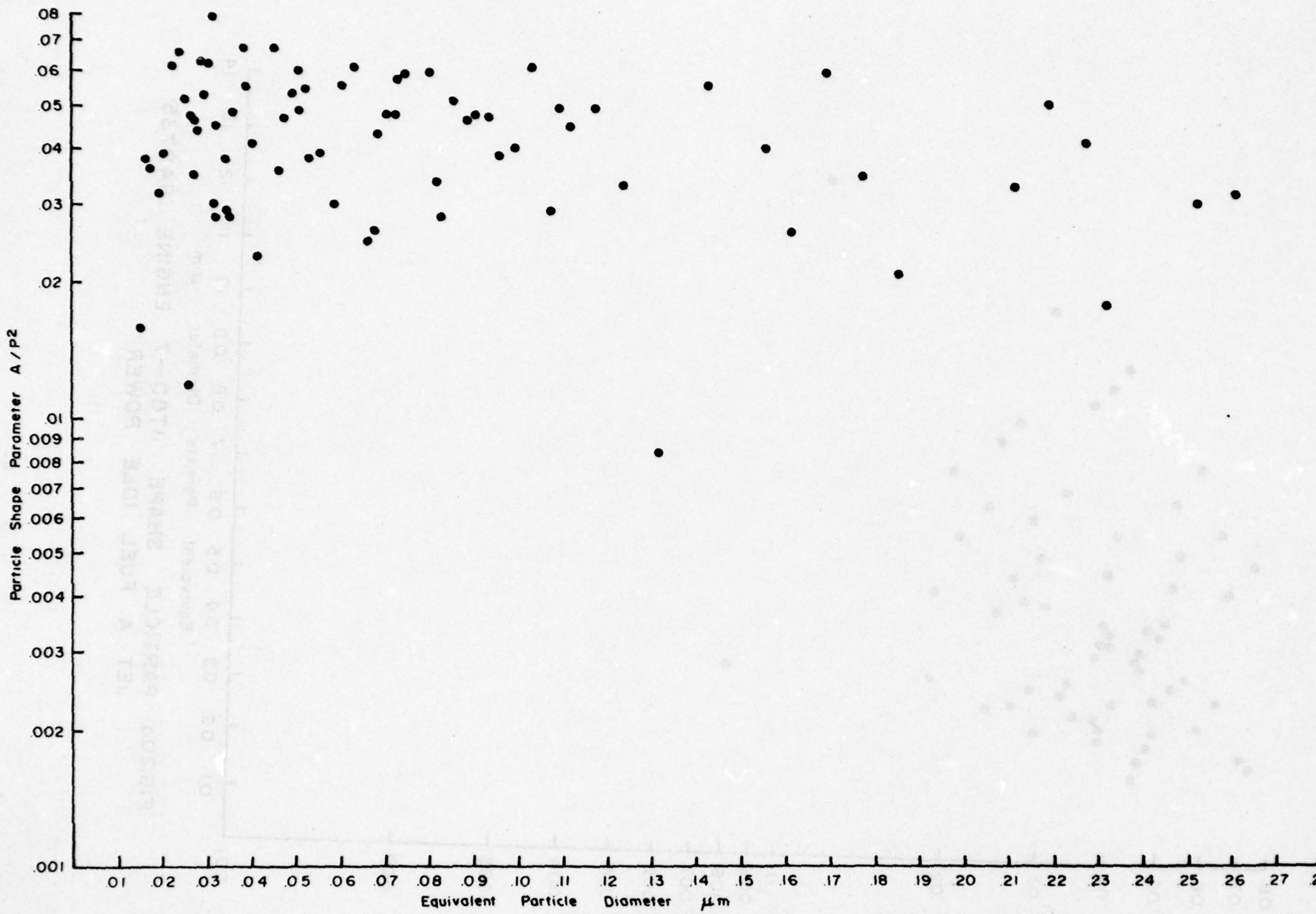


FIG.20b PARTICLE SHAPE JT8D—7 ENGINE 648735 JET A FUEL APPROACH POWER

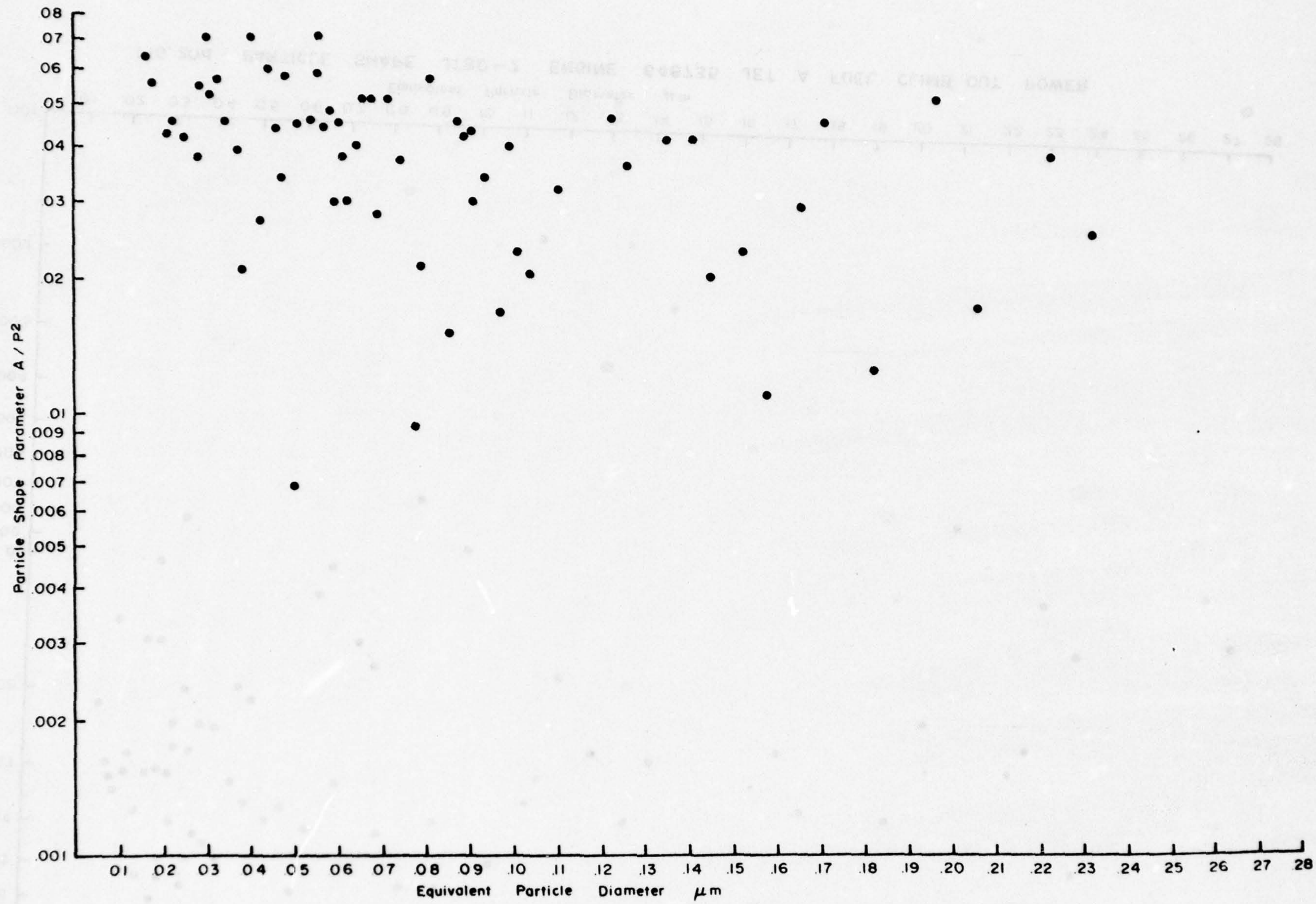


FIG.20c PARTICLE SHAPE JT8D-7 ENGINE 648735 JET A FUEL CRUISE POWER

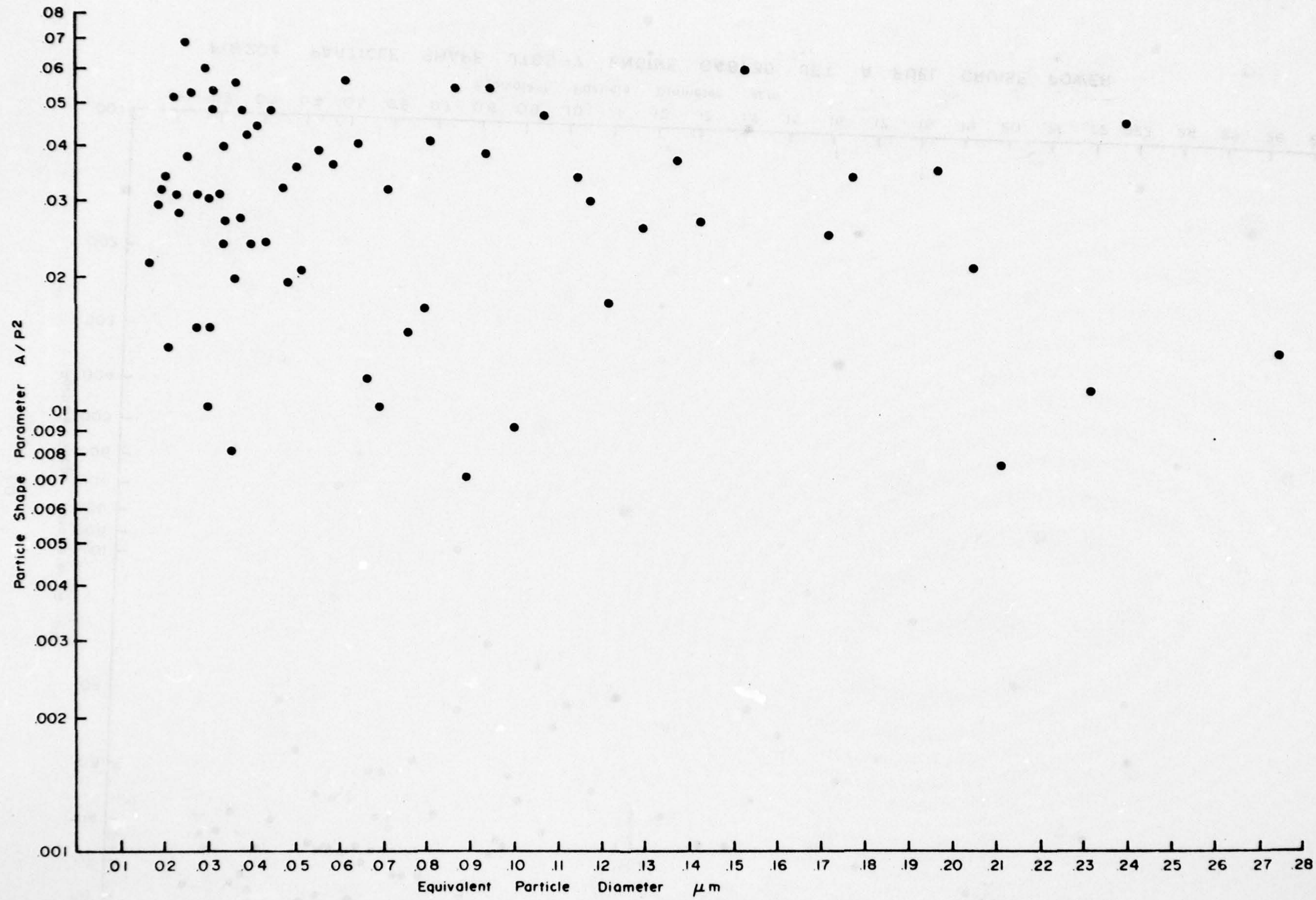


FIG. 20d PARTICLE SHAPE JT8D-7 ENGINE 648735 JET A FUEL CLIMB OUT POWER

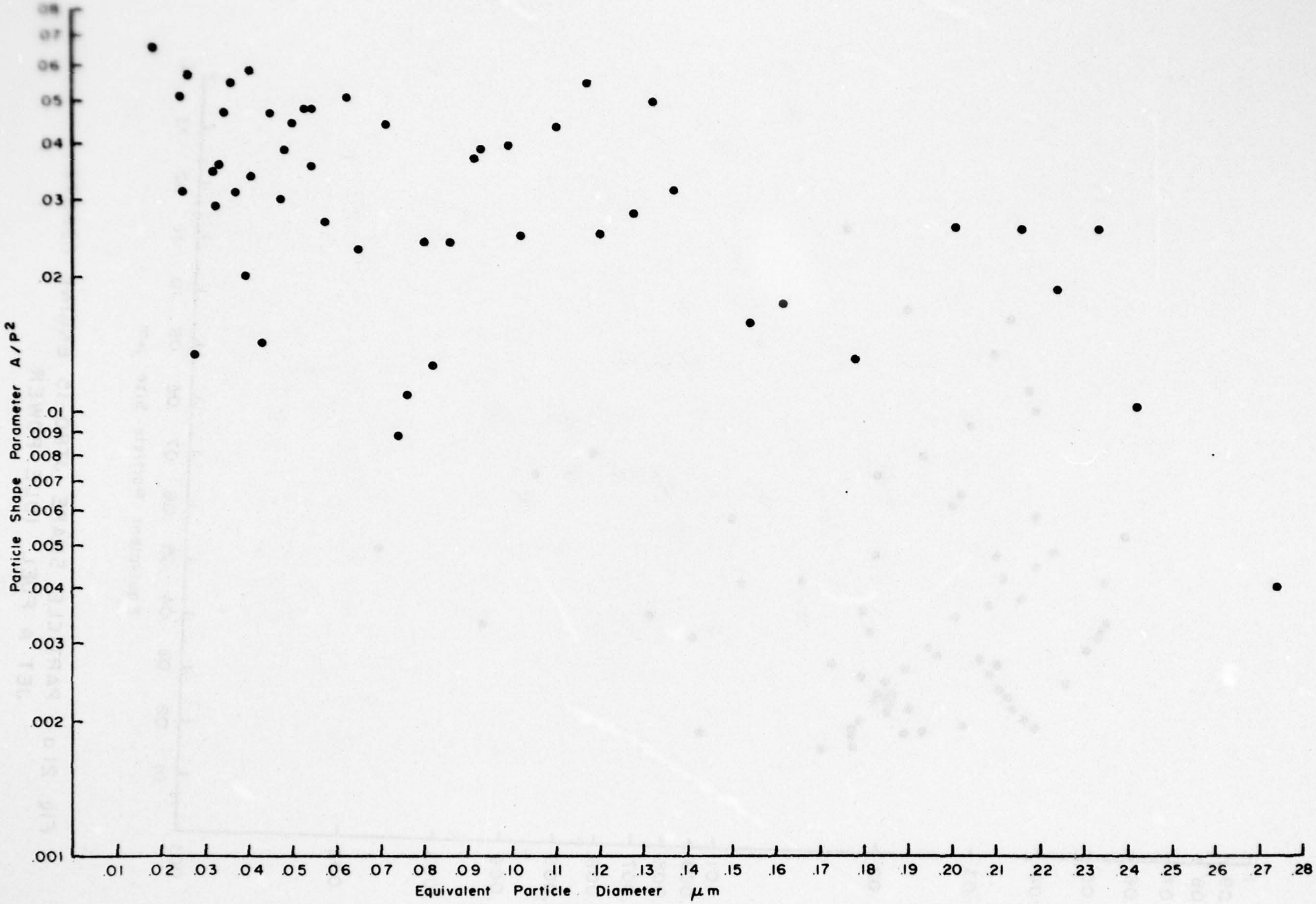


FIG.20e PARTICLE SHAPE JT8D-7 ENGINE 648735 JET A FUEL TAKEOFF POWER

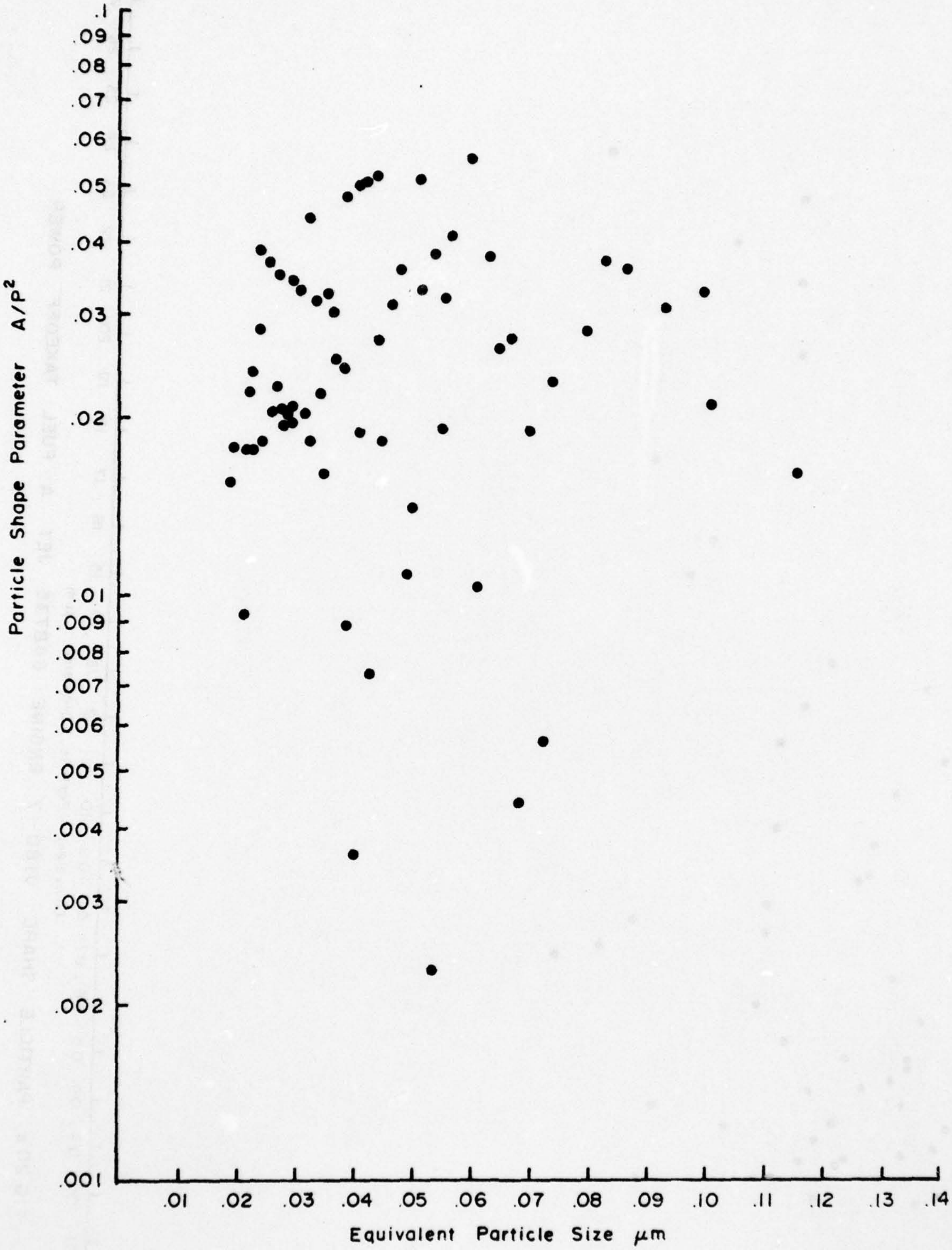


Fig. 21a PARTICLE SHAPE JT8D-15 ENGINE 696572
JET A FUEL IDLE POWER

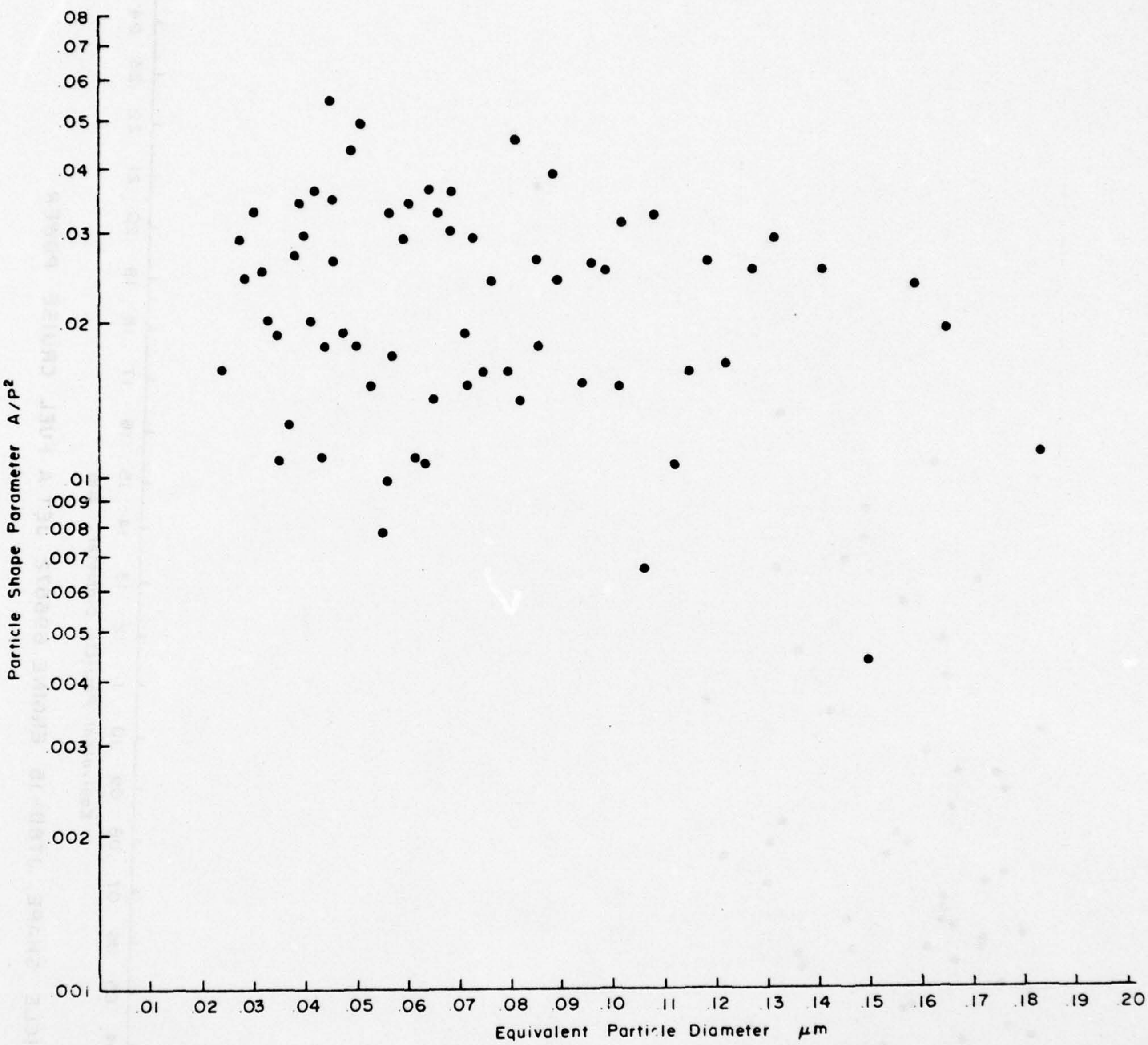


Fig. 21 b PARTICLE SHAPE JT8D-15 ENGINE 696572 JET A FUEL APPROACH POWER

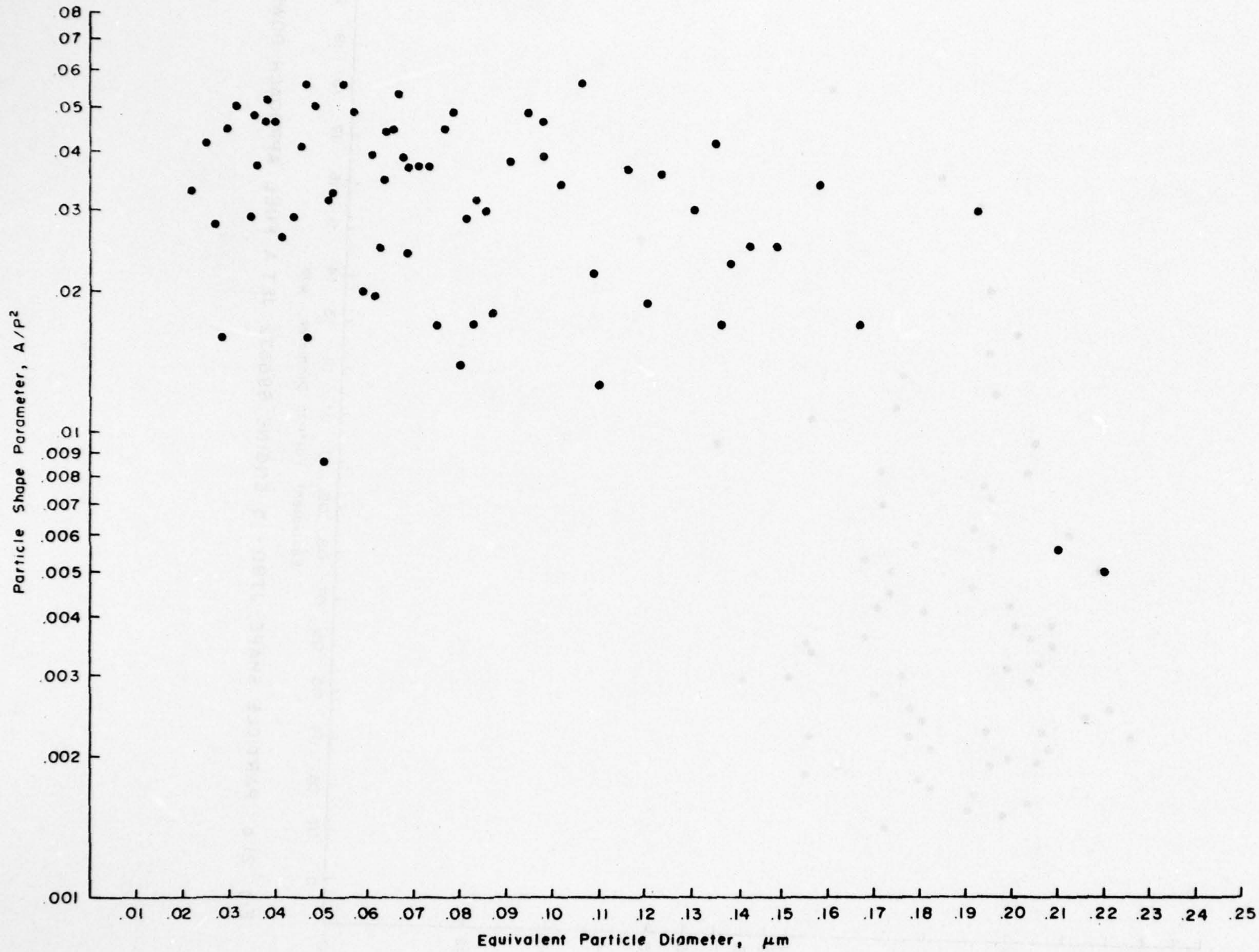


Fig. 21c PARTICLE SHAPE JT8D-15 ENGINE 696572 JET A FUEL CRUISE POWER

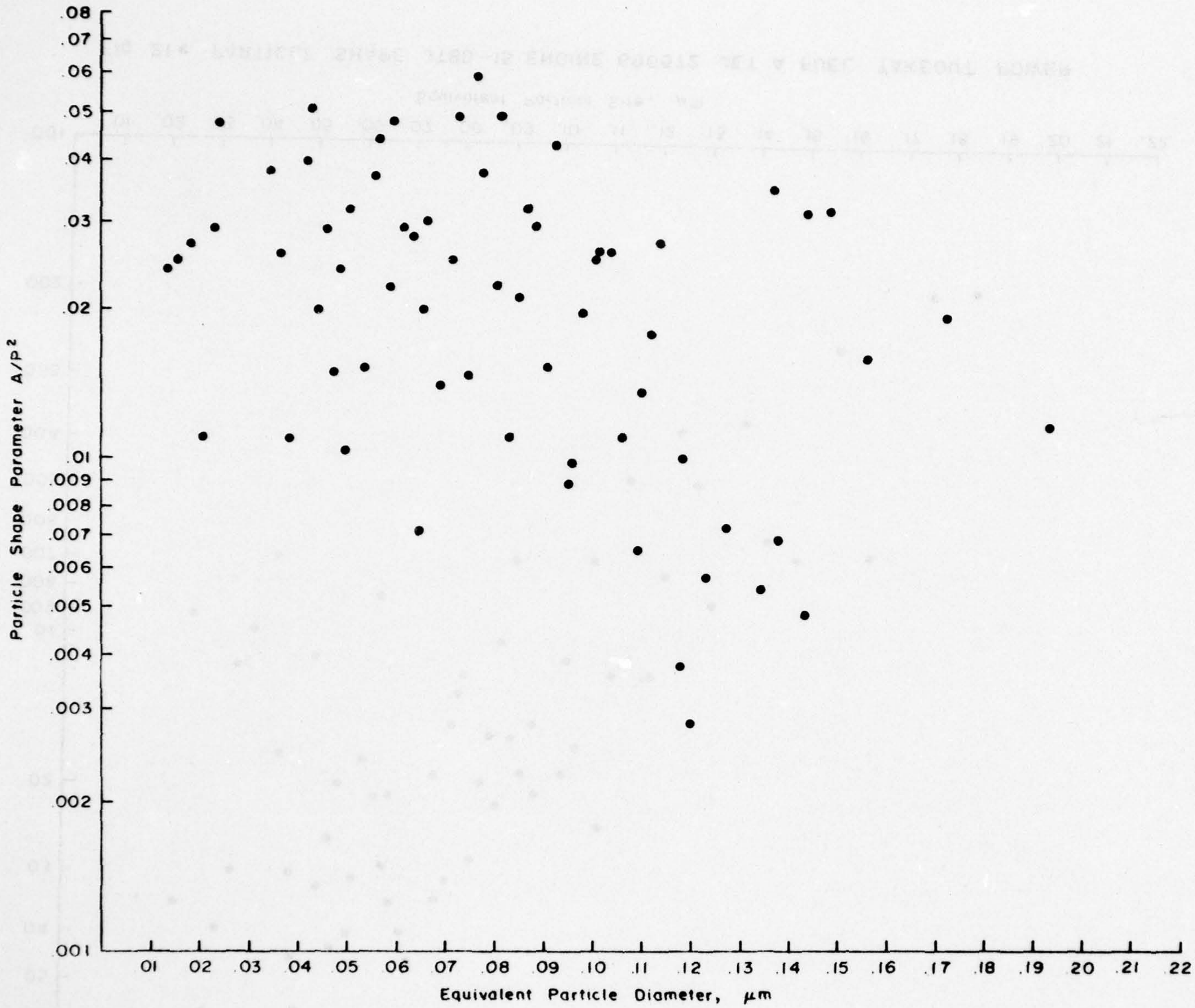


Fig. 21 d PARTICLE SHAPE JT8D-15 ENGINE 696572 JET A FUEL CLIMBOUT POWER

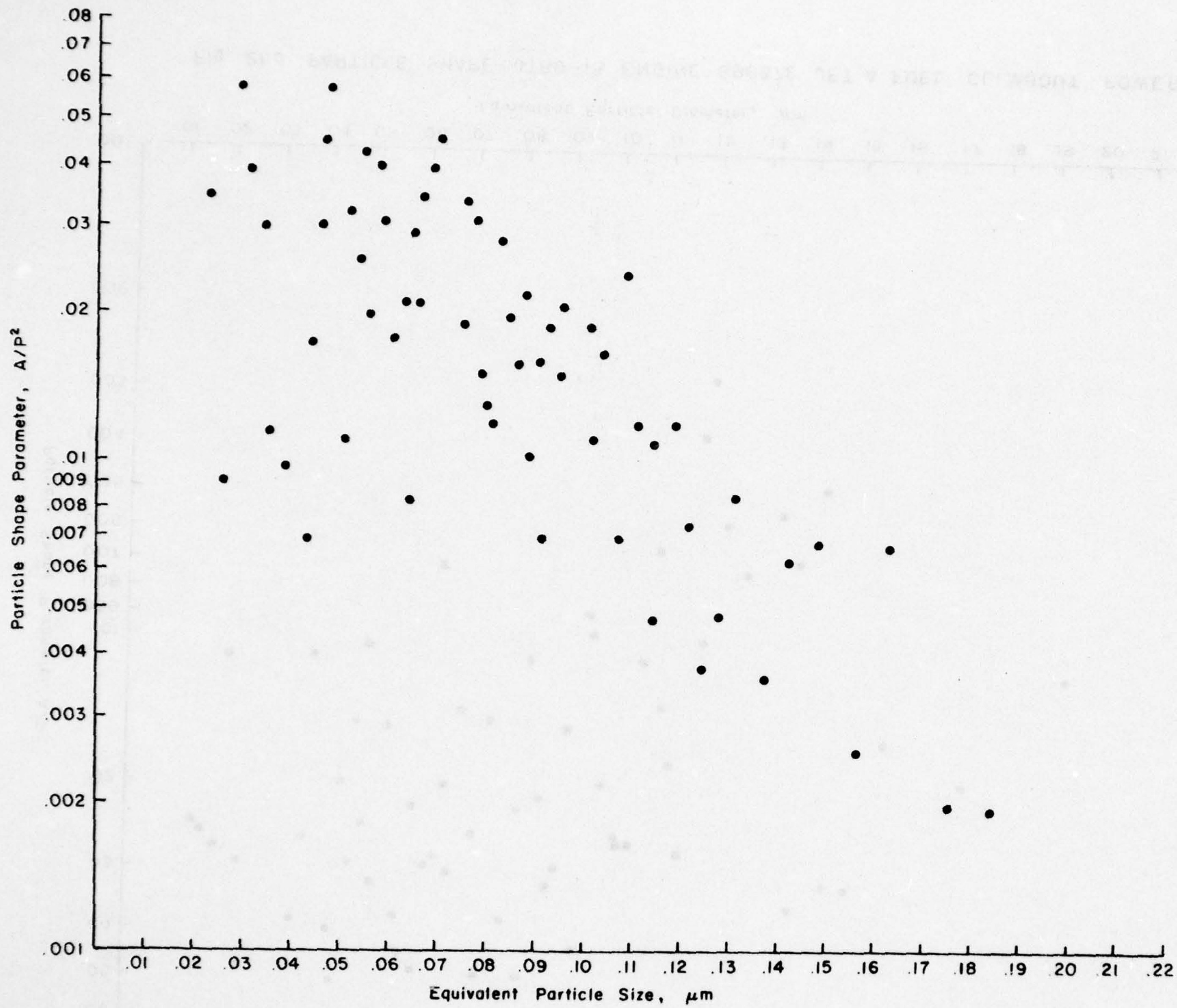


Fig. 21e PARTICLE SHAPE JT8D-15 ENGINE 696572 JET A FUEL TAKEOUT POWER

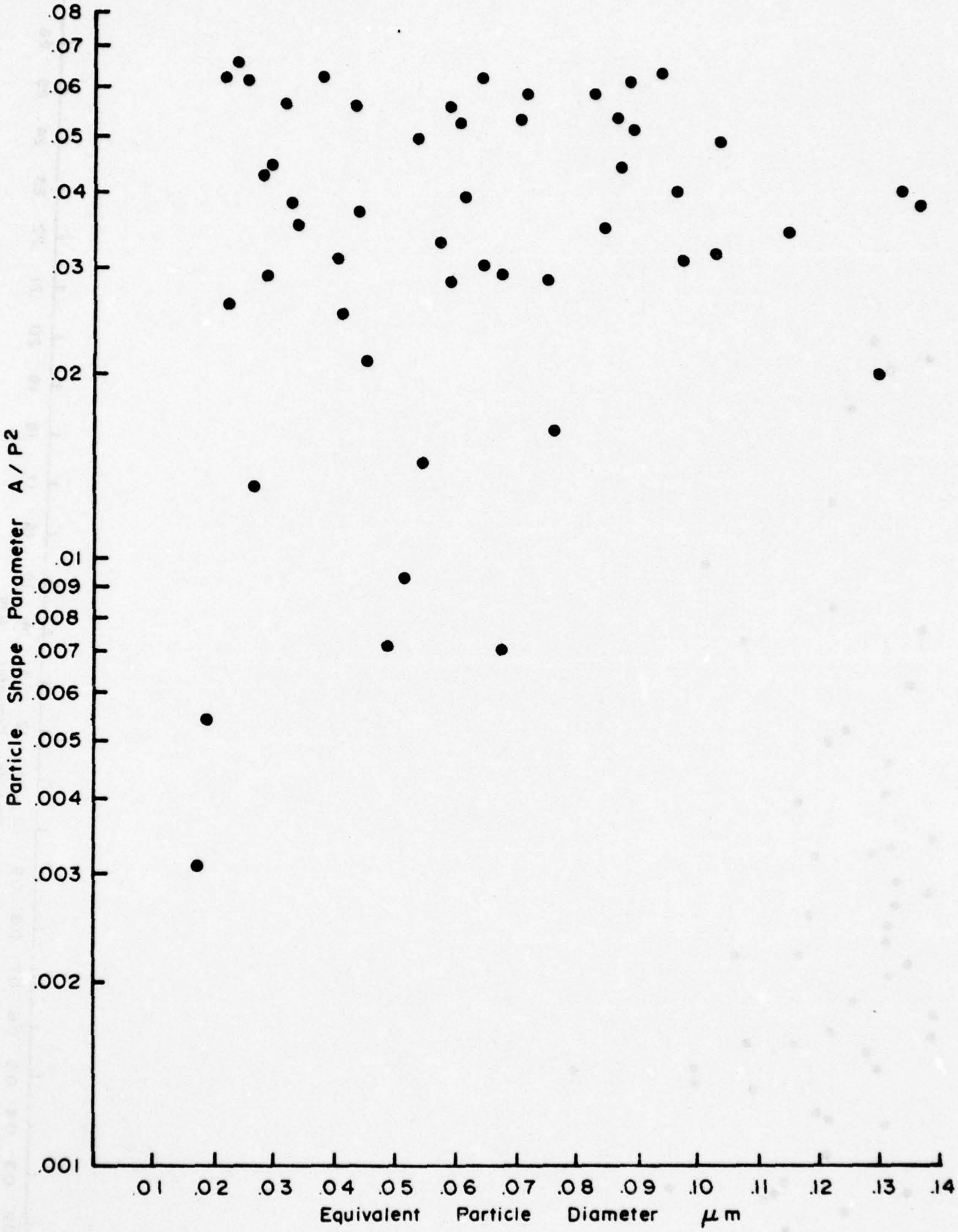


FIG.22a PARTICLE SHAPE JT9D ENGINE 663031
JET A FUEL APPROACH POWER

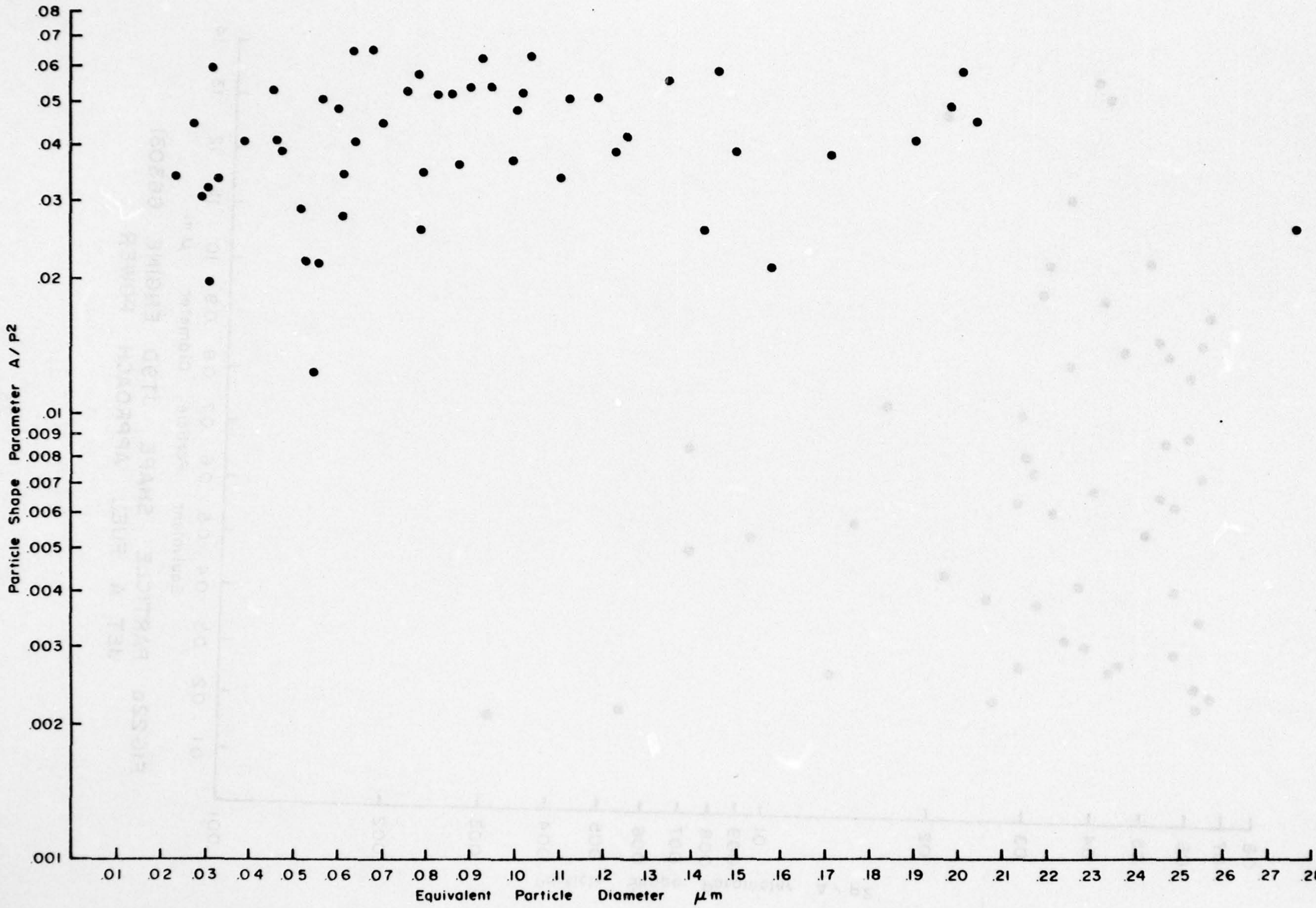


FIG.22 b PARTICLE SHAPE JT9D ENGINE 663031 JET A FUEL TAKEOFF POWER

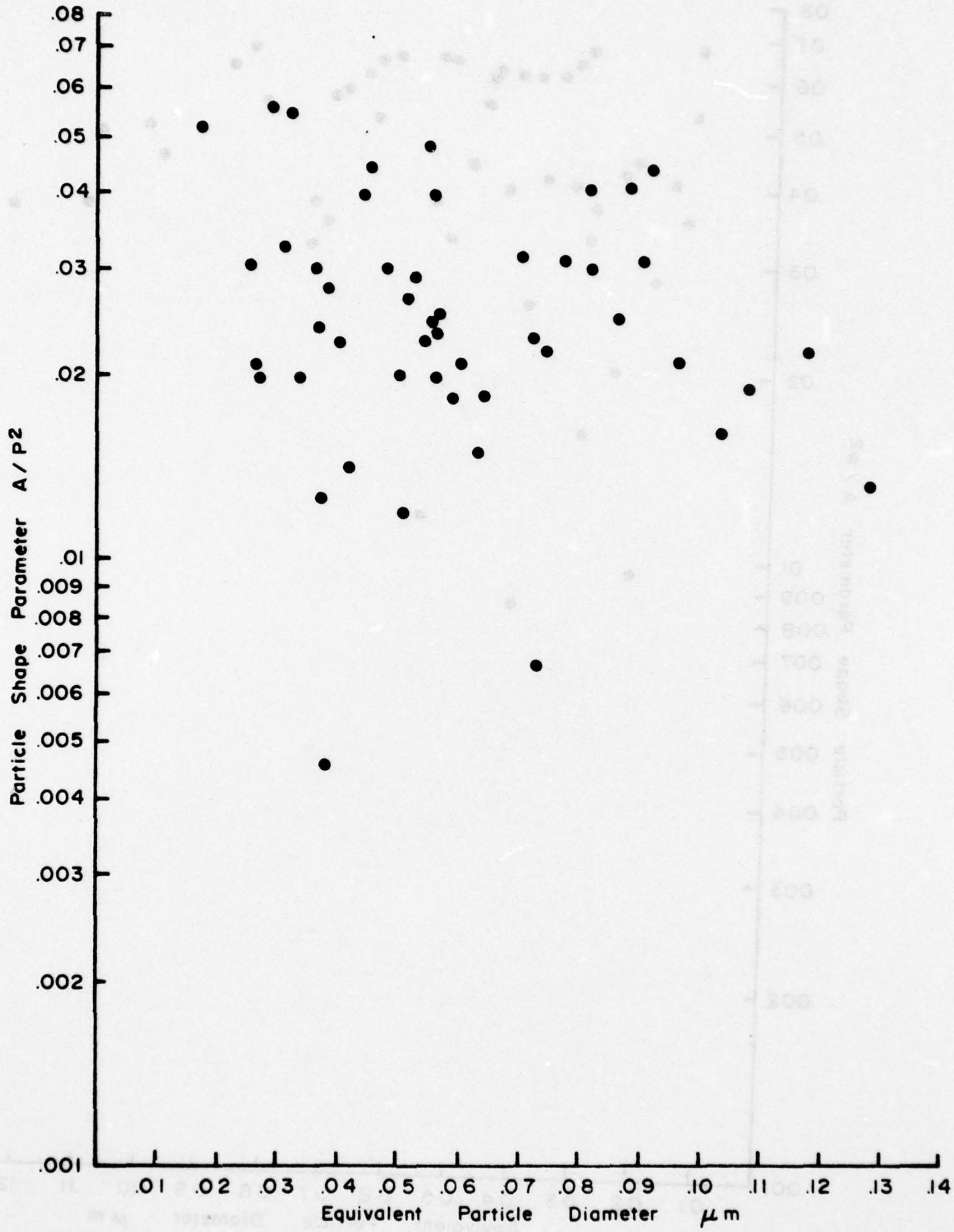


FIG. 23a PARTICLE SHAPE JT9D ENGINE 663031
PK FUEL APPROACH POWER

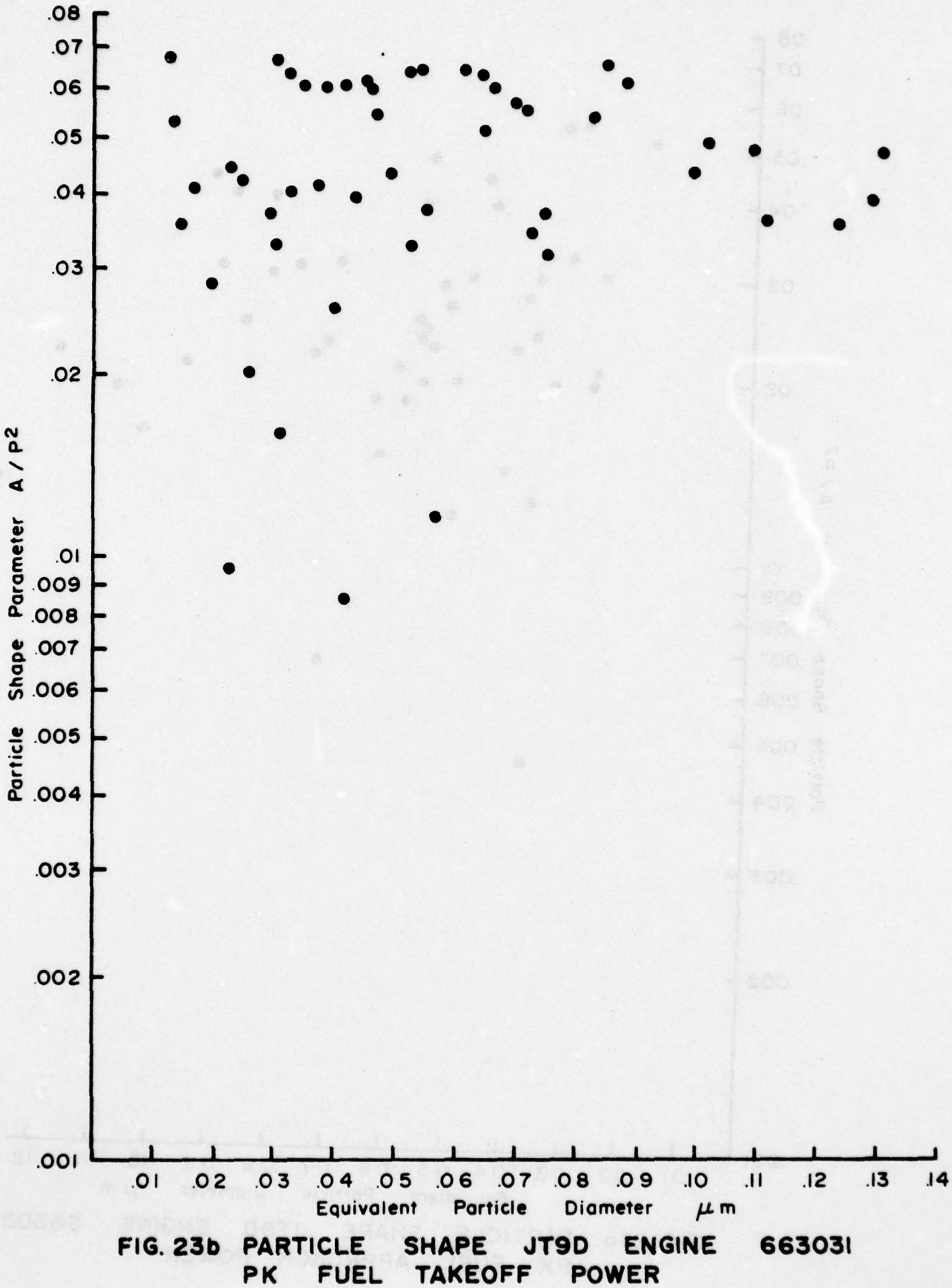


FIG. 23b PARTICLE SHAPE JT9D ENGINE 663031
PK FUEL TAKEOFF POWER

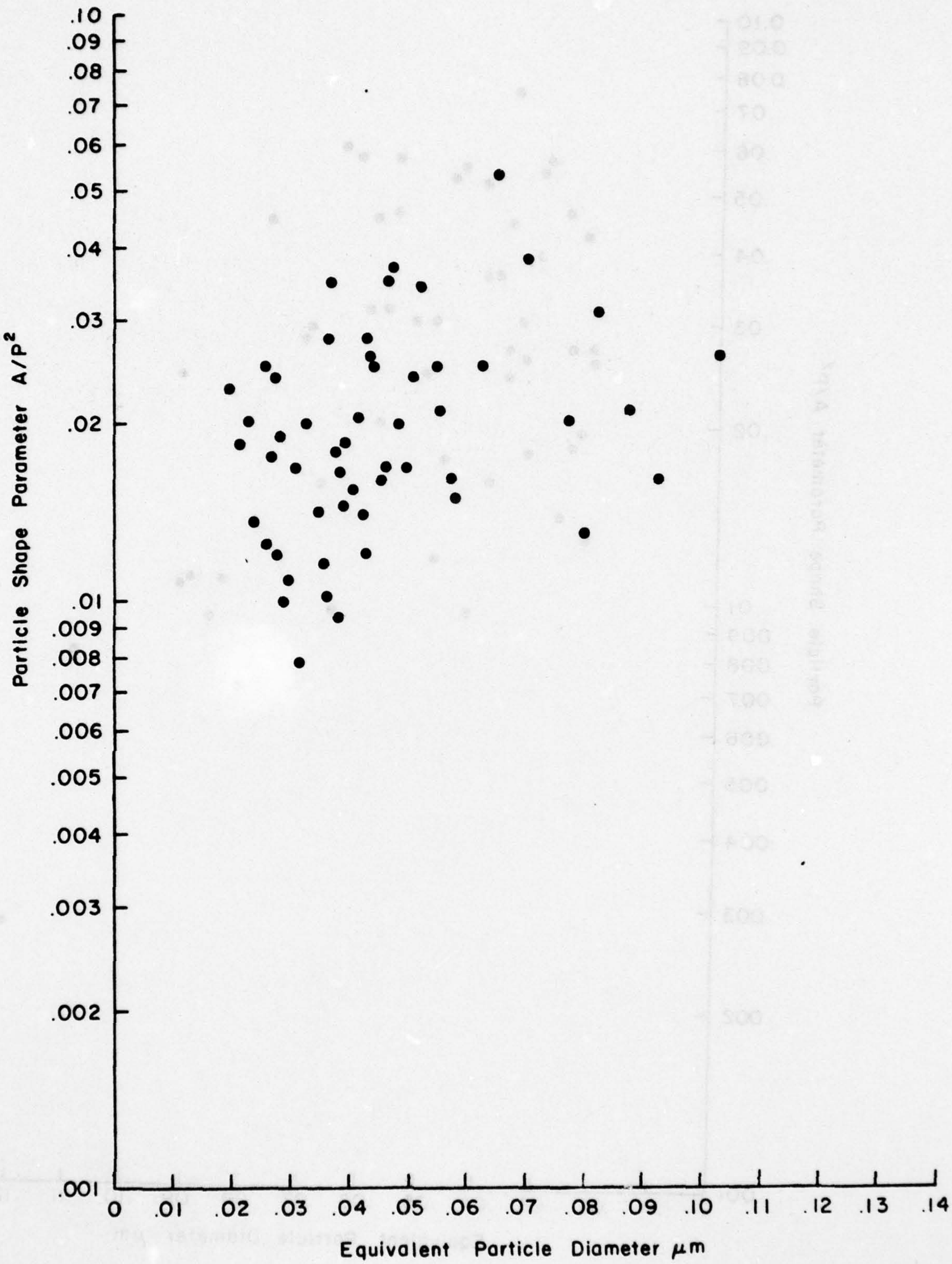


Fig. 24a PARTICLE SHAPE JT9D ENGINE 663082
JET A FUEL IDLE POWER

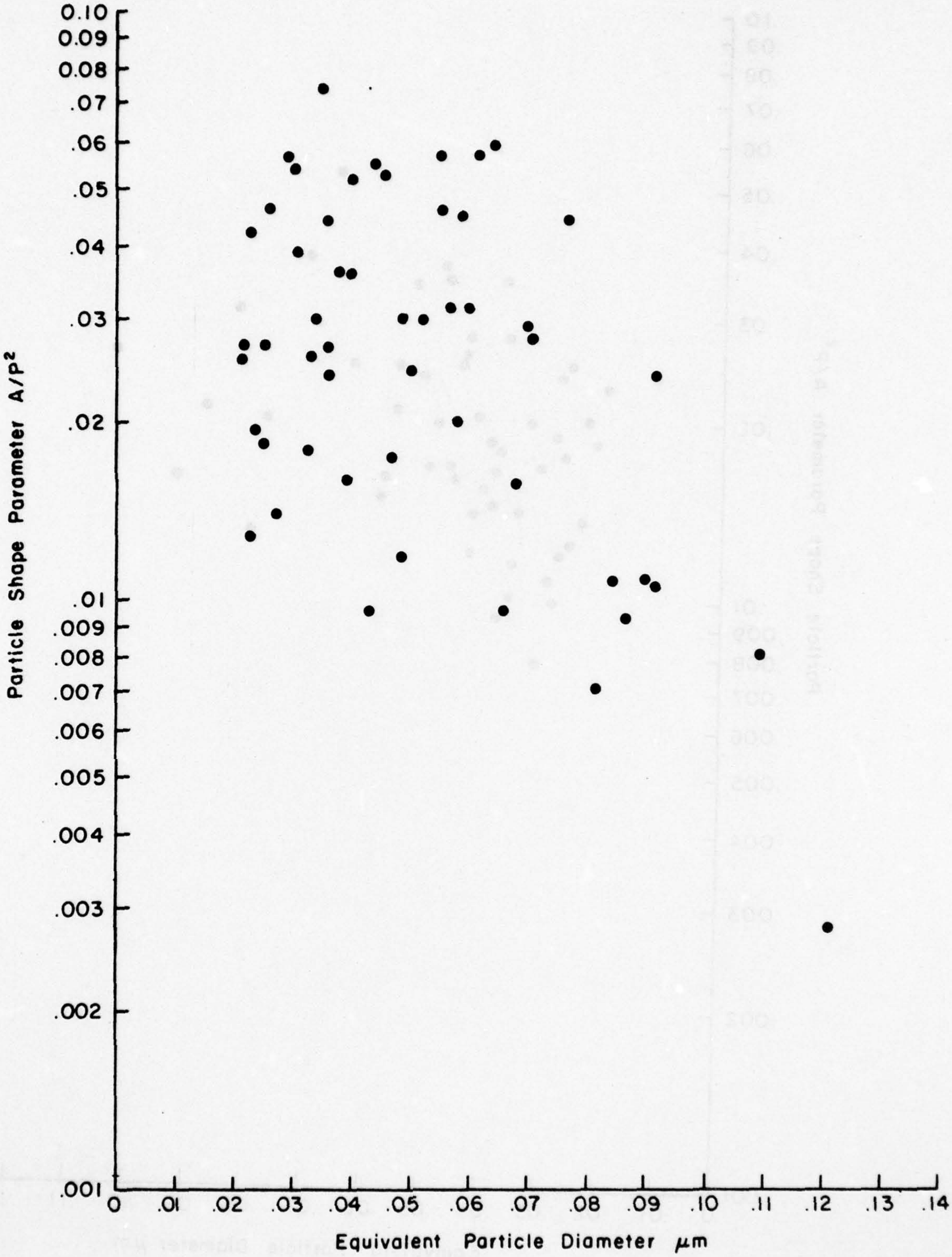


Fig. 24b PARTICLE SHAPE JT9D ENGINE 663082
JET A FUEL APPROACH POWER

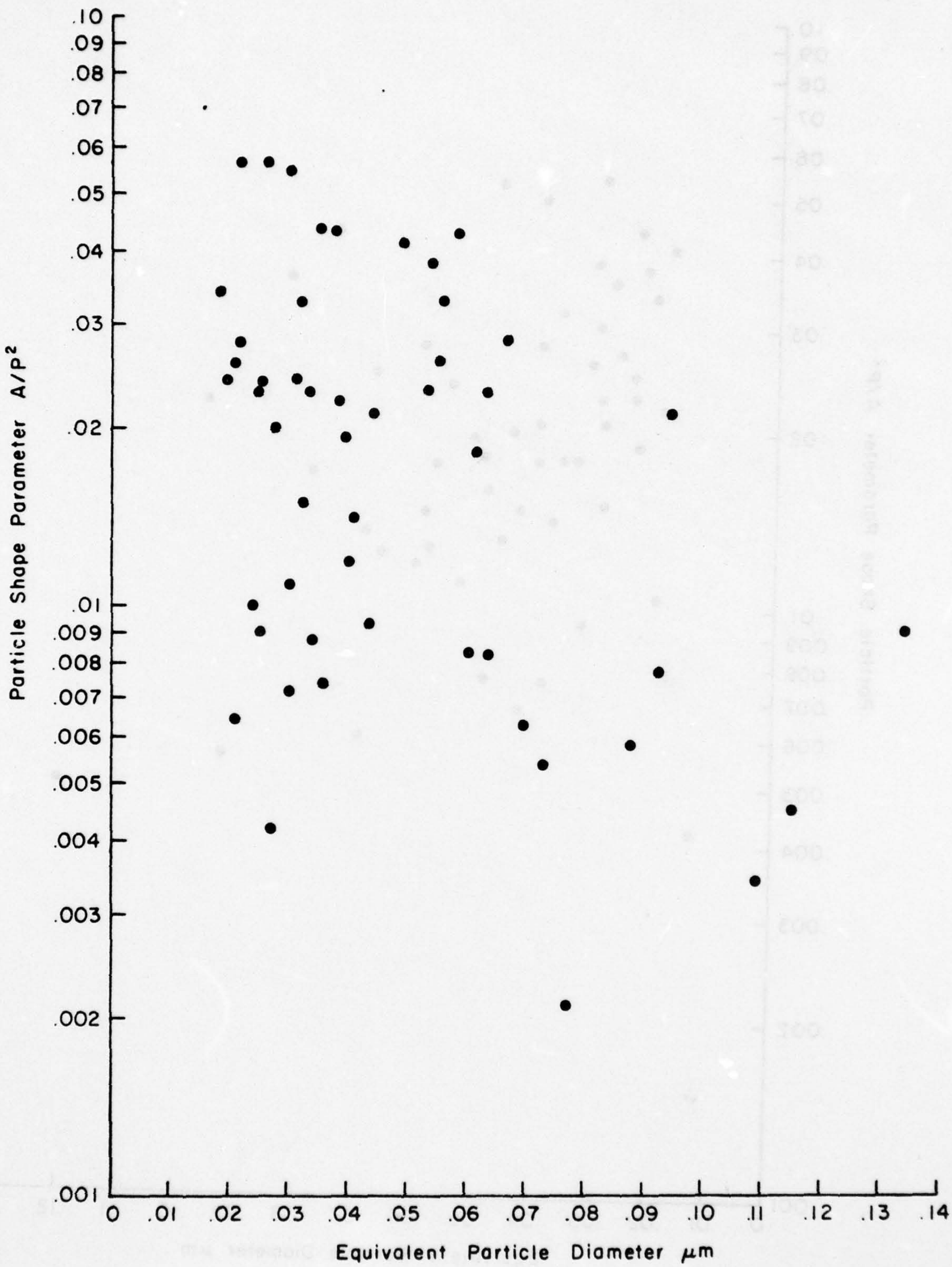


Fig. 24c PARTICLE SHAPE JT9D ENGINE 663082
JET A FUEL CLIMBOUT POWER

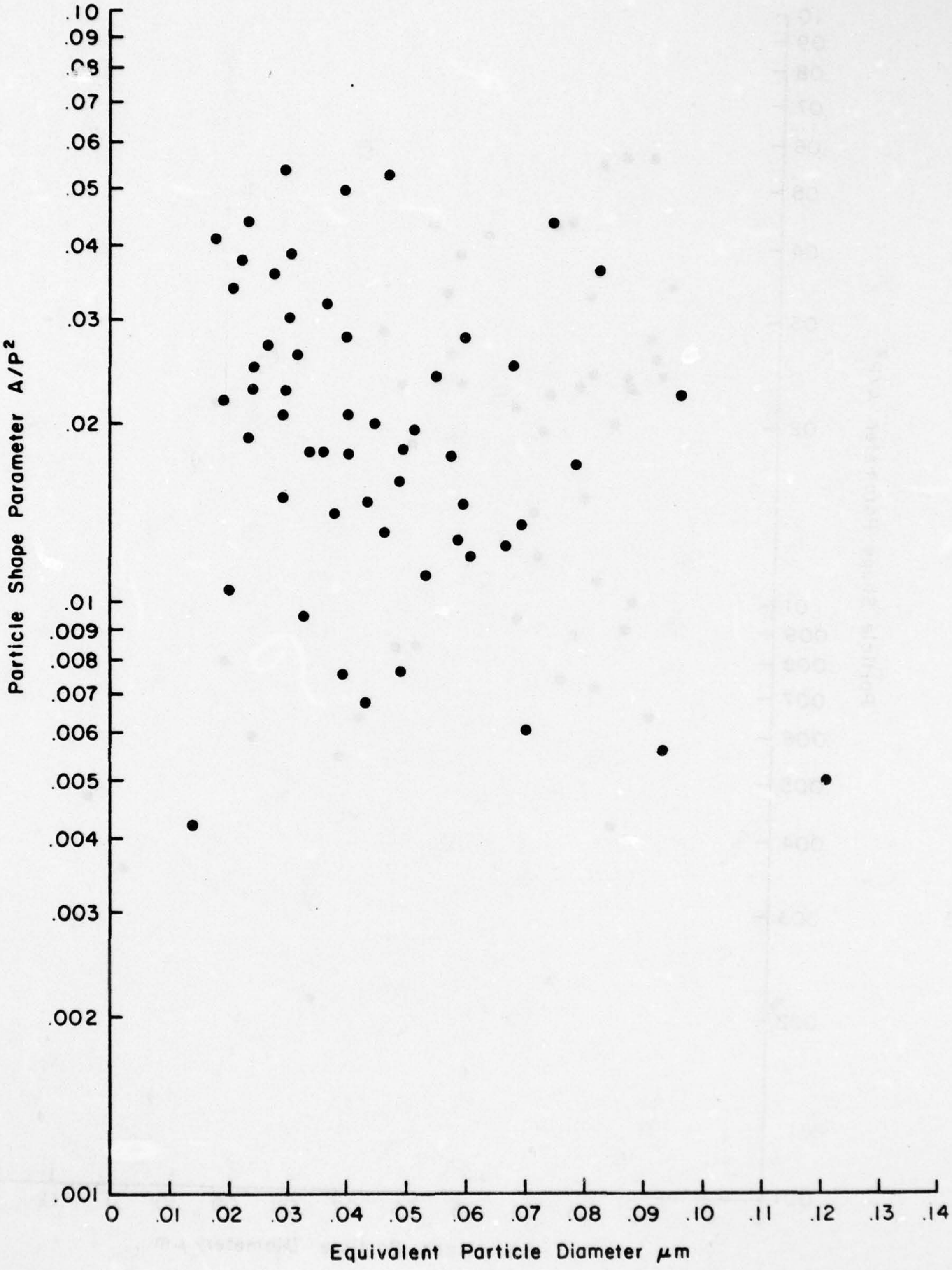
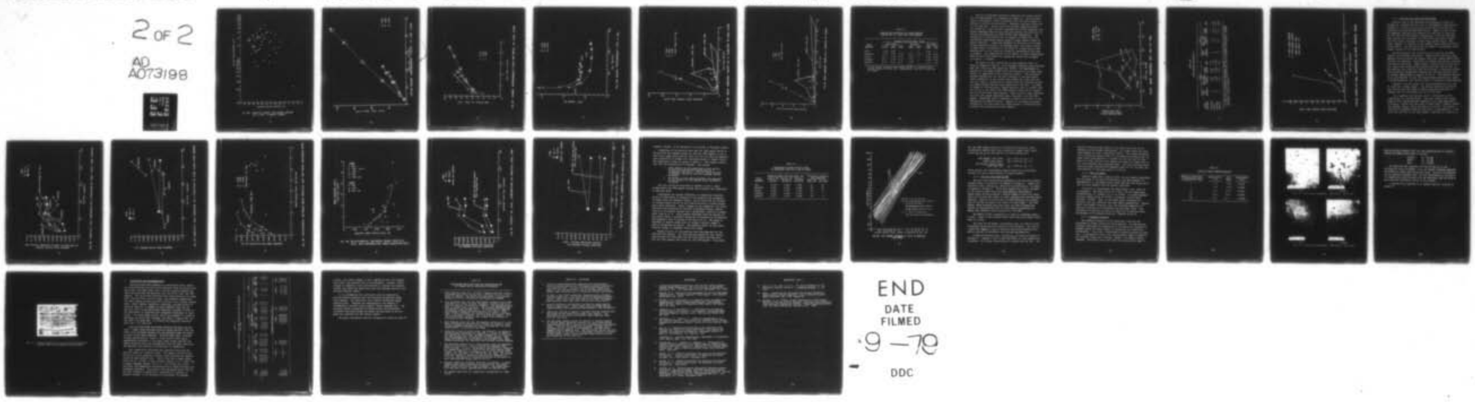


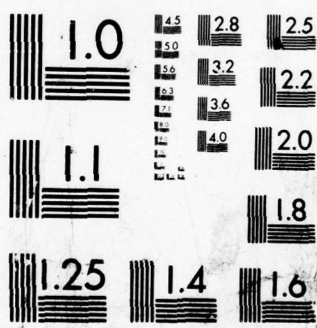
Fig. 25a PARTICLE SHAPE JT9D ENGINE 662794
JET A FUEL CRUISE POWER

AD-A073 198 IIT RESEARCH INST CHICAGO IL F/G 21/5
TURBINE ENGINE PARTICULATE EMISSION CHARACTERIZATION. (U)
JAN 79 J D STOCKHAM, E H LUEBCKE, D L FENTON DOT-FA75-WA3722
UNCLASSIFIED IITRI-C6352-33 FAA-RD-79-15 NL

2 OF 2
AD
A073198



END
DATE
FILMED
9-79
DDC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

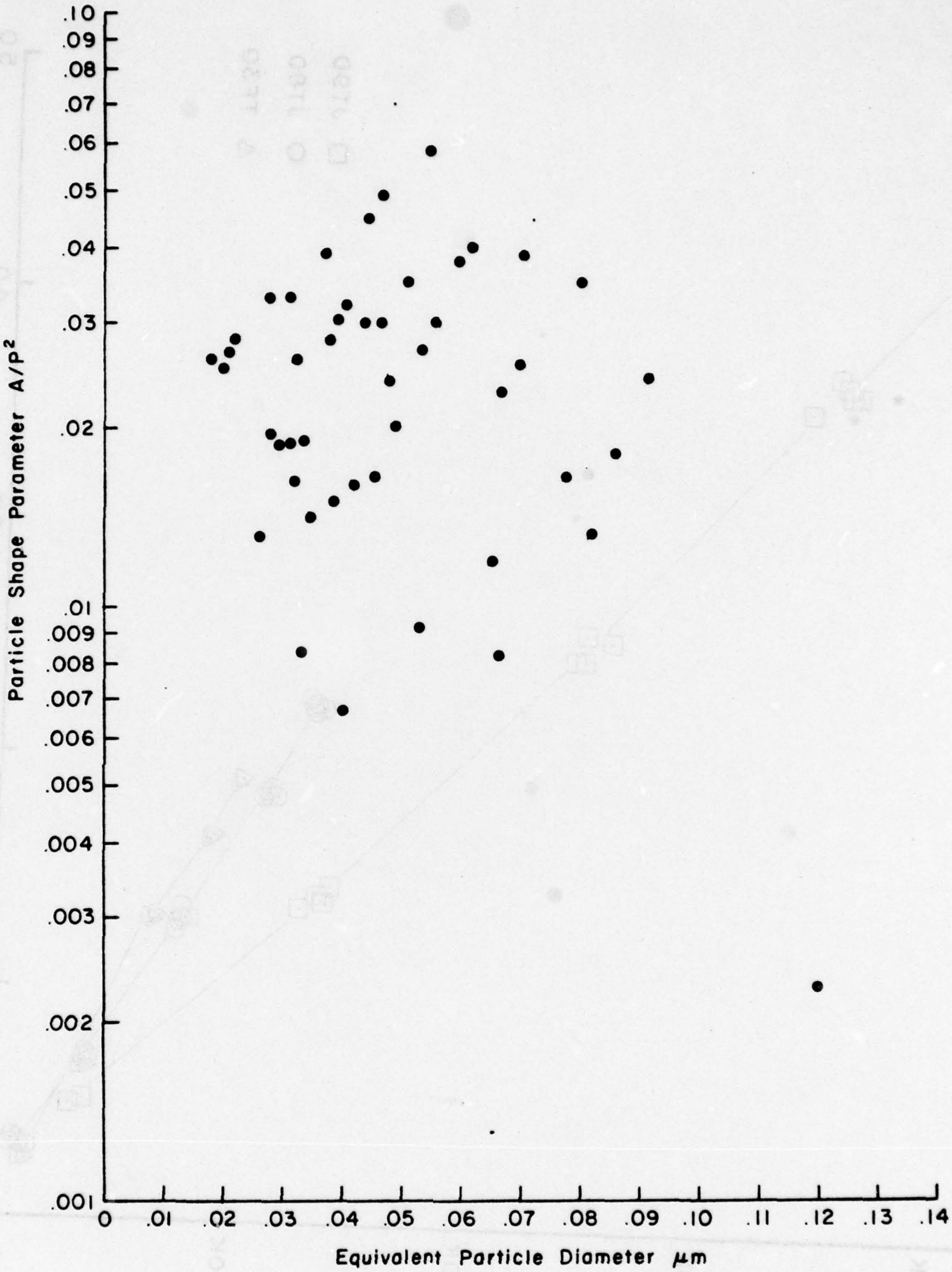


Fig. 25 b PARTICLE SHAPE JT9D ENGINE 662794
JET A FUEL CLIMBOUT POWER

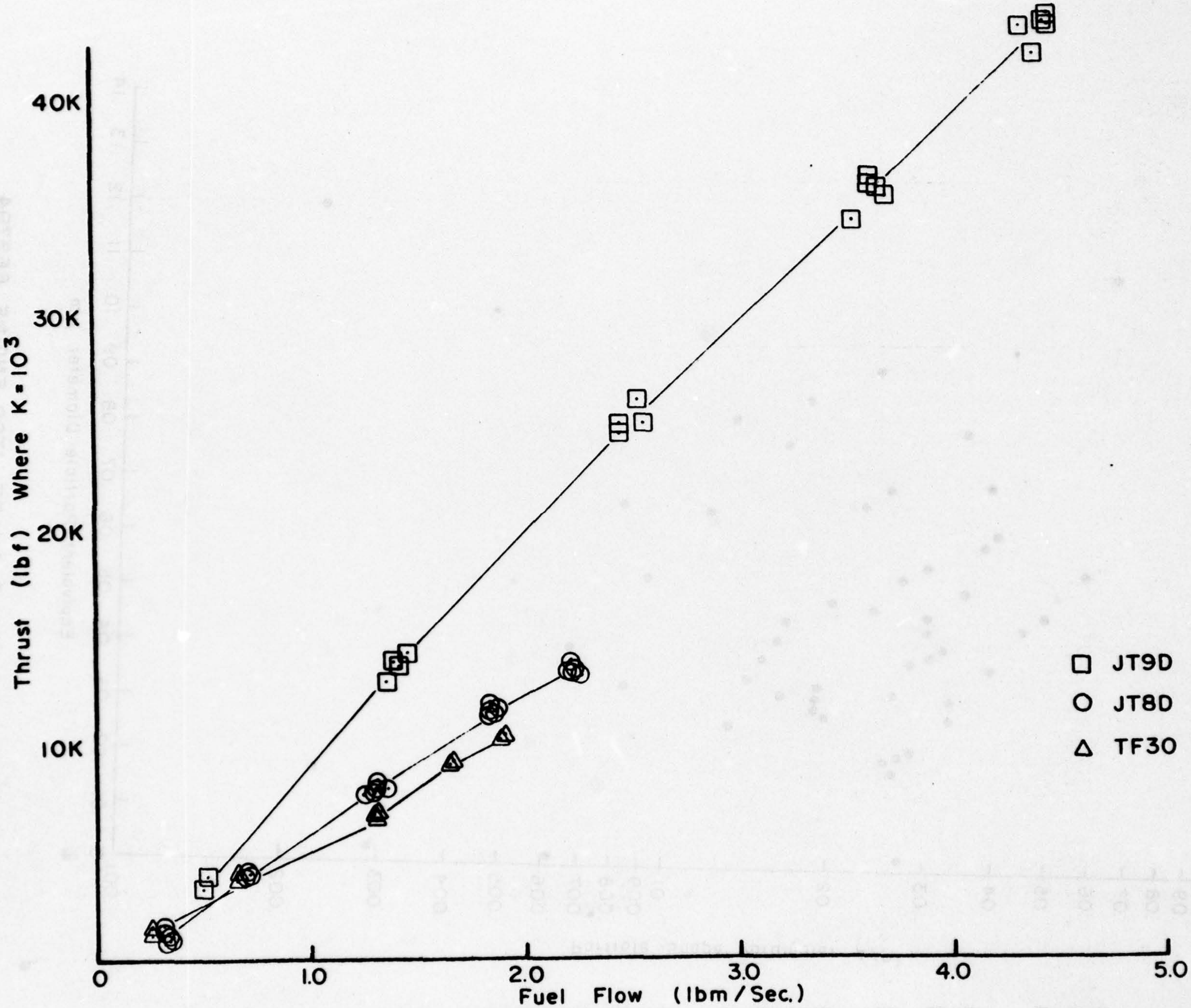


FIG. 26 ENGINE PERFORMANCE — THRUST VS FUEL FLOW

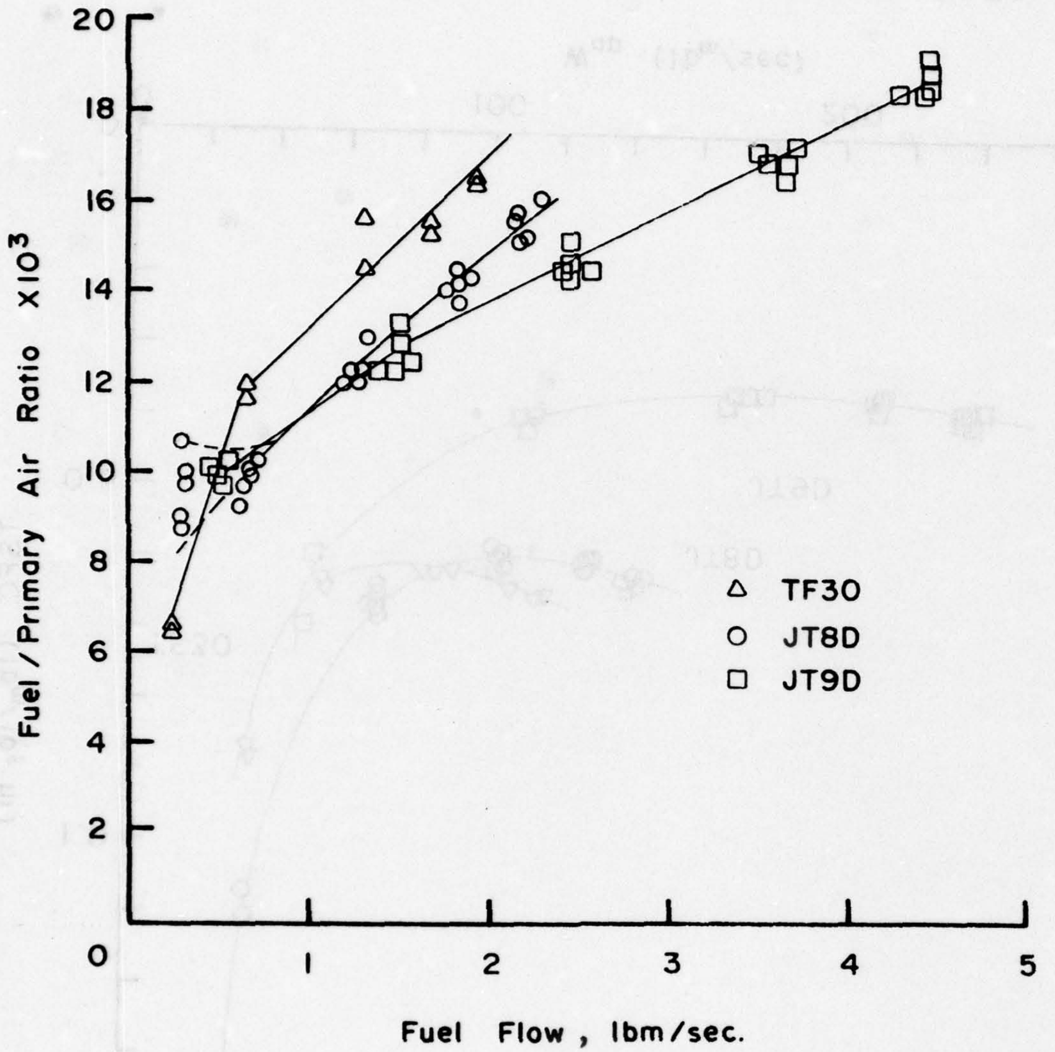


FIG. 27 ENGINE PERFORMANCE—FUEL/AIR RATIO VS FUEL FLOW

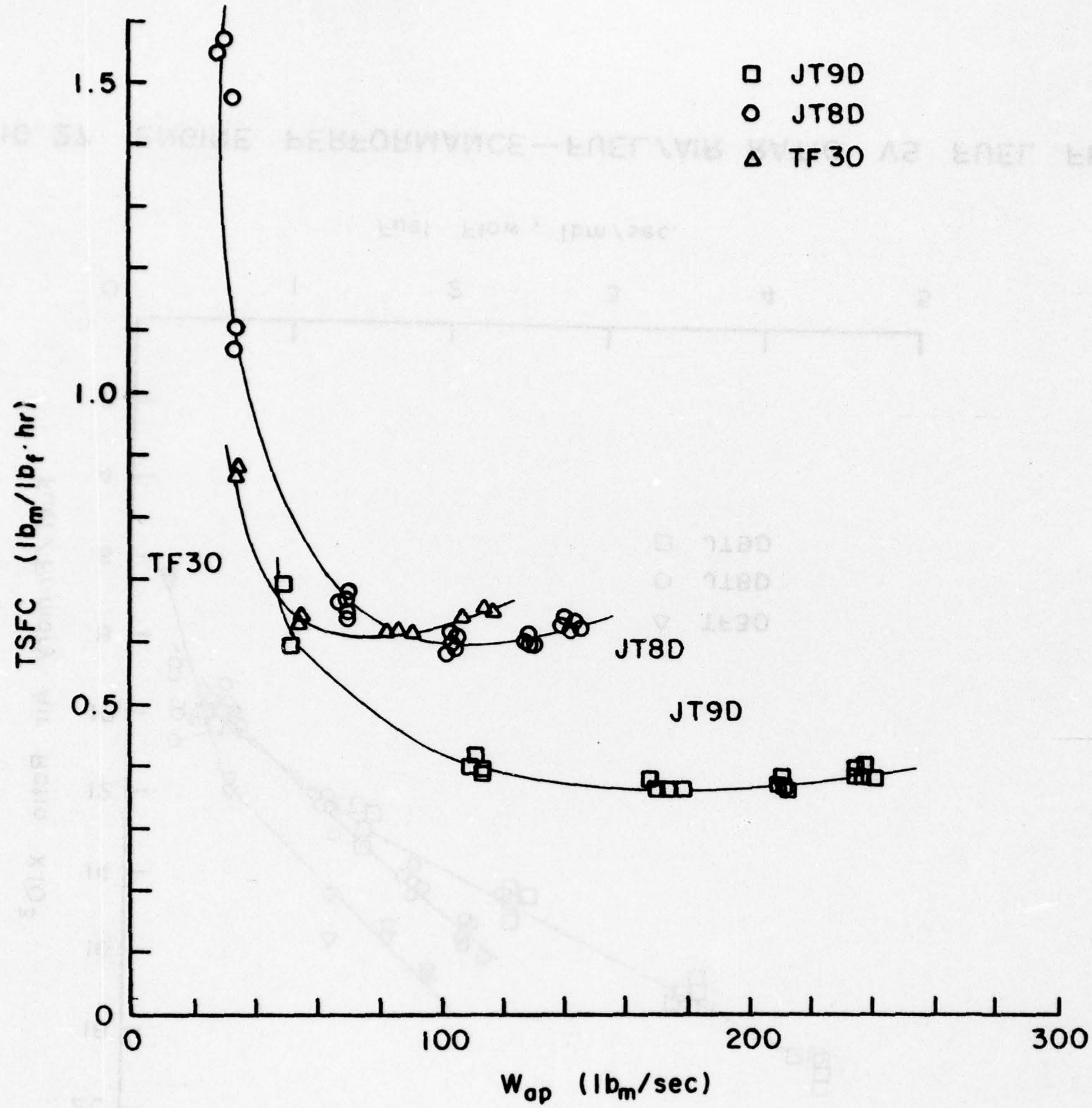


Fig. 28 ENGINE PERFORMANCE - TSFC vs W_{ap}

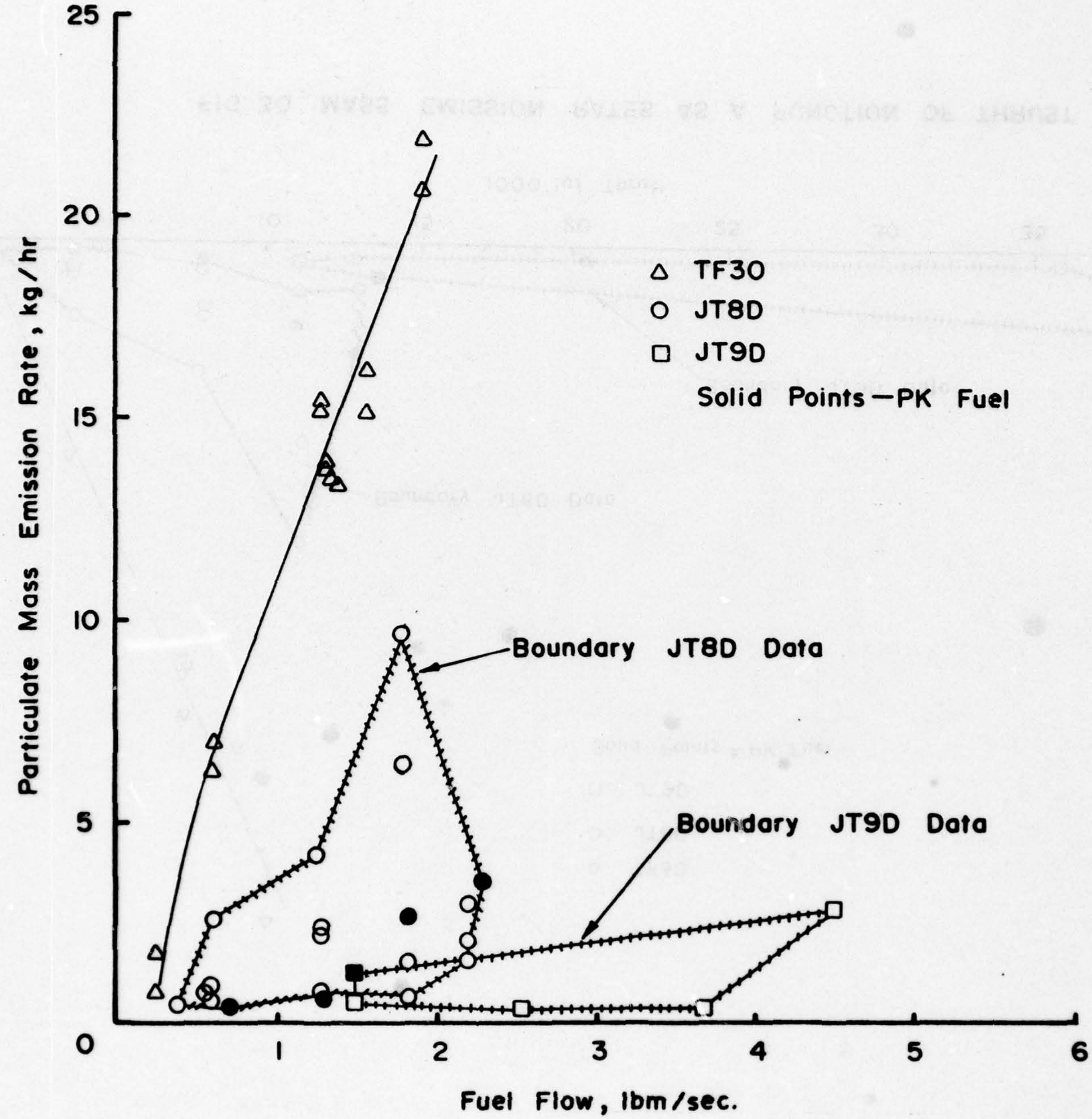


FIG. 29 MASS EMISSION RATES AS A FUNCTION OF FUEL FLOW

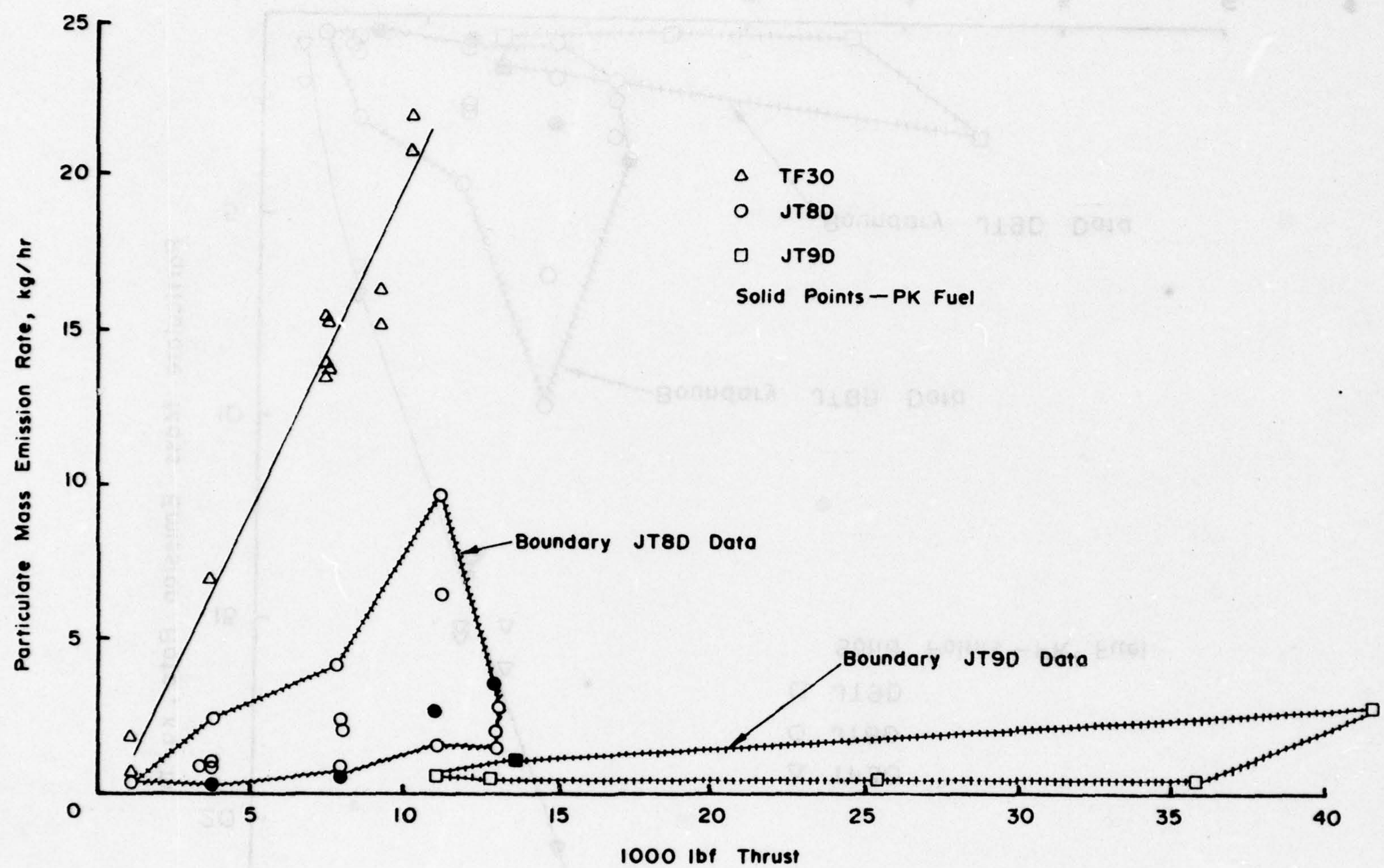


FIG. 30 MASS EMISSION RATES AS A FUNCTION OF THRUST

Table 17

AVERAGE MASS EMISSIONS BY POWER SETTING
FOR THE TF-30, JT8D, AND JT9D ENGINES

	Average Emission Rate, kg/hr						
	JET A Fuel			PK Fuel		All Fuels	
Power Setting	TF-30	JT8D	JT9D	JT8D	JT9D	JT8D	JT9D
Idle	1.28	0.40	--	--	--	0.40	--
Approach	6.70	1.82	0.49	0.21	1.10	1.50	0.80
Cruise	14.4	2.30	0.33	0.52	--	1.95	0.33
Climbout	15.8	4.60*	0.32	2.70	--	4.22*	0.32
Takeoff	21.5	2.14	2.8	3.45	--	2.47	2.80

* If the result obtained from engine 648796 is rejected these values become 2.85 and 2.82, respectively, for JET A fuel and all fuels.

Lack of a consistent pattern of emissions with power setting for the JT8D engines is illustrated in Figure 31. This inconsistency is believed to result principally from the small amount of material collected on the filters. Sampling times were restricted by time and cost. Future tests with extended sampling periods are needed for a more accurate determination of mass emission rates. Longer sampling times are also desirable because the particles are emitted intermittently as puffs rather than continuously. The variability of the present data is compared in Table 18 to the variability experienced among a group of eight engines tested at Pratt & Whitney.[13] Using the parameter of the ratio of the range of mass emission values to the average value, the present series of data shows a variability on the order of 5 times greater than reported by P & W at climb and cruise but approximately the same at takeoff. The repeatability of the sampler is amply demonstrated from the TF-30 data where the consecutive cruise data averaged 6.43 kg/hr ± 2 percent.

The effect of fuel composition on mass emission rates is shown in Figures 31 and 32. Pearl Kerosene produced lower emissions than Jet A fuel for JT8D engine No. 648796. The improvement is greatest at the higher power levels and reduced at the lower power levels; in opposition to that found by Shirmer.[14] The consistent emission pattern for the two fuels employed in the same engine lends credibility to the results even though the climb point for the Jet A fuel is suspect and no takeoff data was obtained because the sample filter ruptured upon completion of the test. As shown in Figure 31, PK fuel gave a higher emission level at takeoff than Jet A fuel on the other three JT8D engines tested and at climbout for two of the other three engines. Pearl K gave a higher emission level for the single comparison point, approach, with the JT9D engine. Additional data is required to resolve the effect of fuel composition on emission levels. Because of the engine-to-engine variability, the data taken on a single engine is considered more reliable than comparisons between engines.

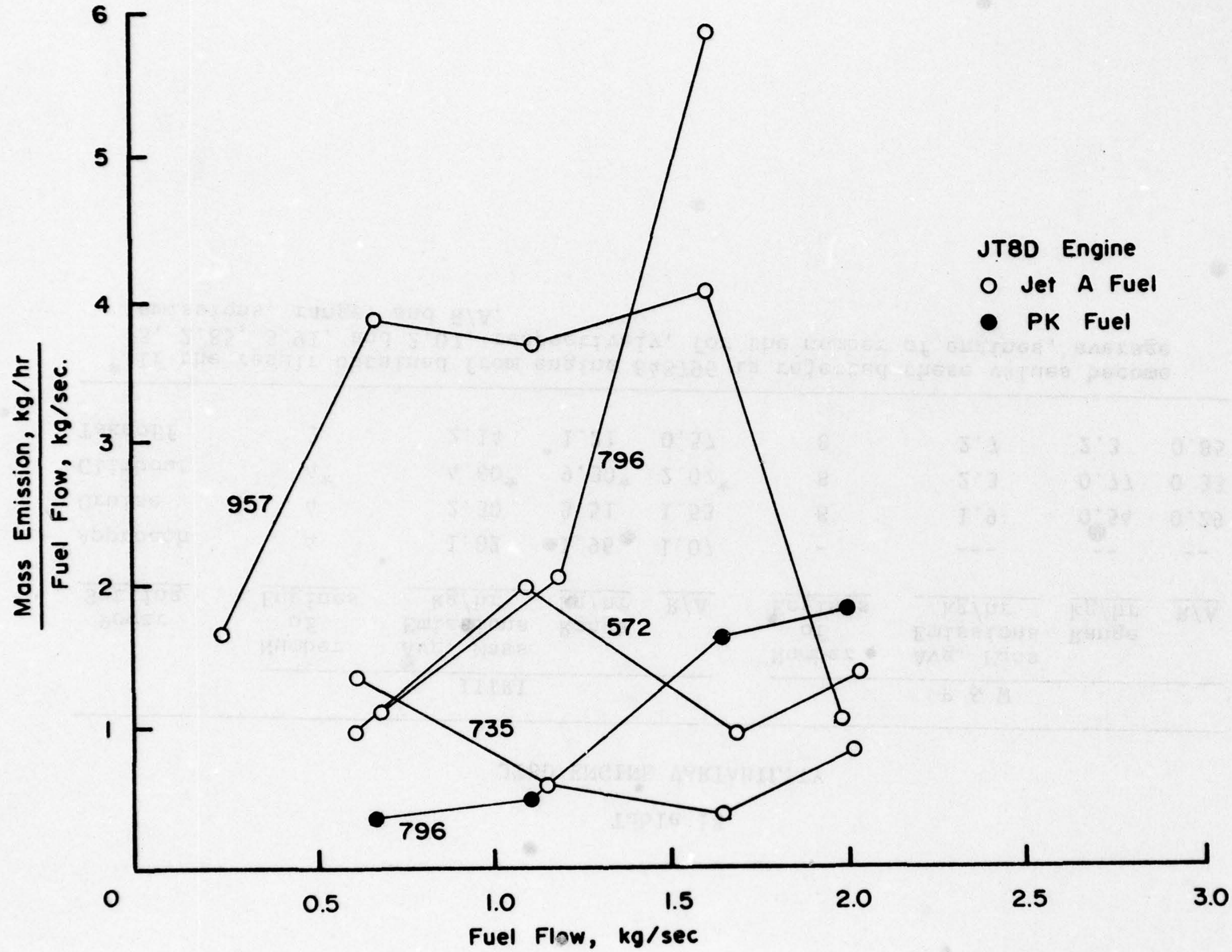


FIG. 31 MASS EMISSIONS PER UNIT OF FUEL

Table 18

JT8D ENGINE VARIABILITY

	IITRI				P & W			
Power Setting	Number of Engines	Avg. Mass Emissions kg/hr	Range kg/hr	R/A	Number of Engines	Avg. Mass Emissions kg/hr	Range kg/hr	R/A
Approach	4	1.82	1.96	1.07	-	---	--	--
Cruise	4	2.30	3.51	1.53	8	1.9	0.54	0.29
Climbout	4*	4.60*	9.30*	2.02*	8	2.3	0.77	0.33
Takeoff	3	2.14	1.21	0.57	8	2.7	2.3	0.85

* If the result obtained from engine 648796 is rejected these values become 3, 2.85, 5.91, and 2.07, respectively, for the number of engines, average emissions, range, and R/A.

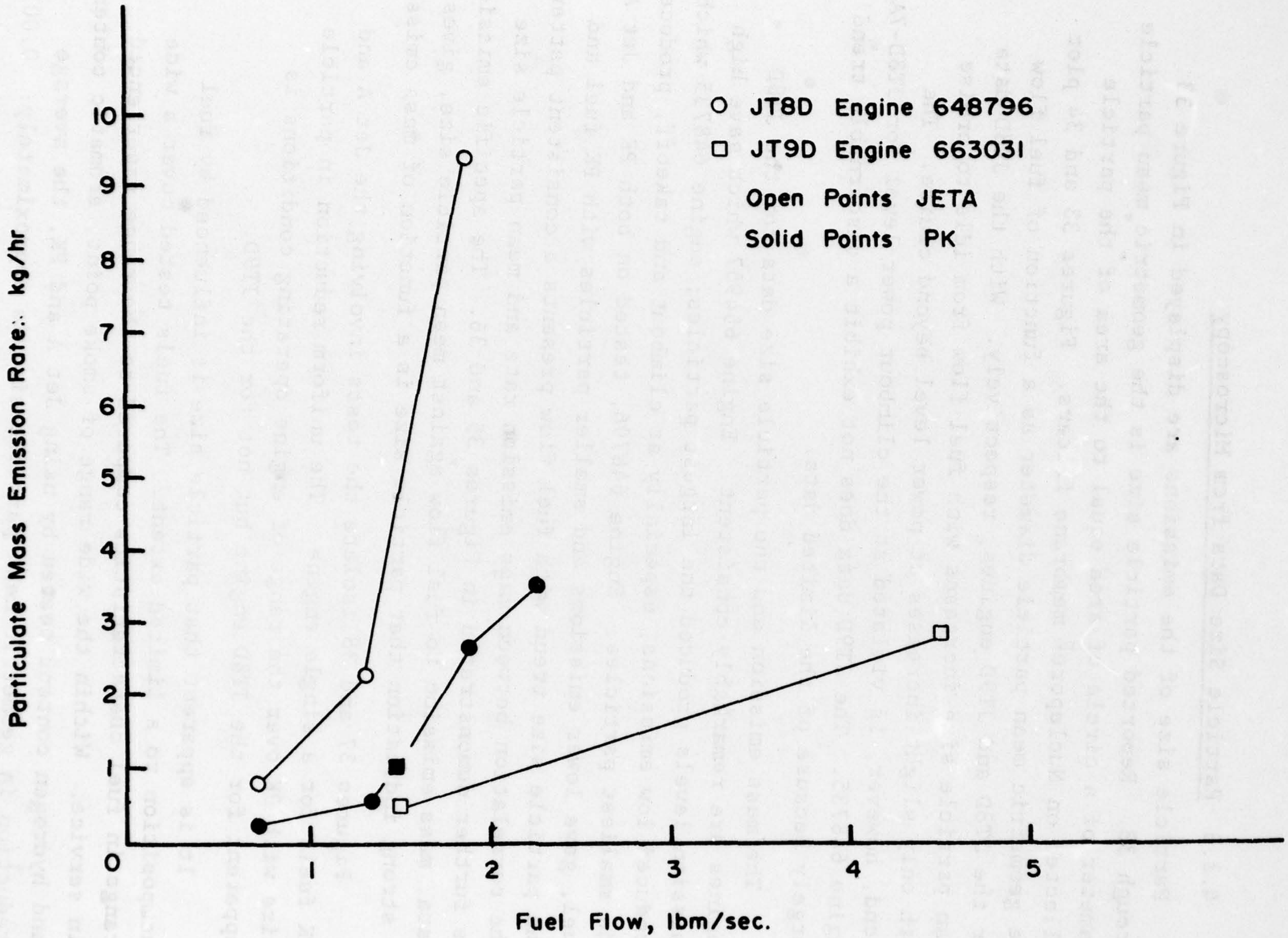


FIG. 32 EFFECT OF FUEL COMPOSITION ON MASS EMISSION RATES

4.2.3 Particle Size Data from Microscopy

Particle size of the emissions are displayed in Figure 33 through 38. Reported particle size is the geometric mean particle diameter of a circle of area equal to the area of the particle collected on Nuclepore^{R} membrane filters. Figures 33 and 34 plot the geometric mean particle diameter as a function of fuel flow for the JT8D and JT9D engines, respectively. With the JT8D data mean particle size increases with fuel flow from idle to cruise with only slight increases at power level beyond cruise. The trend, however, is violated at the climbout power level for JT8D-7A engine 648735. The JT9D data does not exhibit a discernable trend largely because of the limited data.

The mass emission and the particle size data for the JT8D engines are remarkably consistent. Engine 654957 which gave high emission levels produced the largest particles; engine 648735 which produced low emissions, especially at climbout and takeoff, produced the smallest particles. Engine 648796, tested on both PK and Jet A fuel, gave lower emissions and smaller particles with PK fuel and the particle size trend with fuel flow presents a consistent pattern. The correlation between mass emission rate and mean particle size is further demonstrated in Figures 35 and 36. The specific emission data, mass emission to fuel flow against mean particle size, gives a strong indication that particle size is a function of mass emission.

Figures 37 and 38 isolate the tests involving the Jet A and PK fuels for a single engine. The uniform reduction in particle size with PK over the range of engine operating conditions is apparent for the JT8D engine but not for the JT9D.

It is apparent that particle size is influenced by fuel composition to a limited extent. The fuels tested cover a wide range in fuel characteristics compared to the range experienced in service. Within the wide range of smoke point, aromatic content, and hydrogen content tested by using Jet A and PK, the average reduction in geometric mean particle size is approximately: 0.001 μm for an increase of one smoke number, reduction of 1 percent in

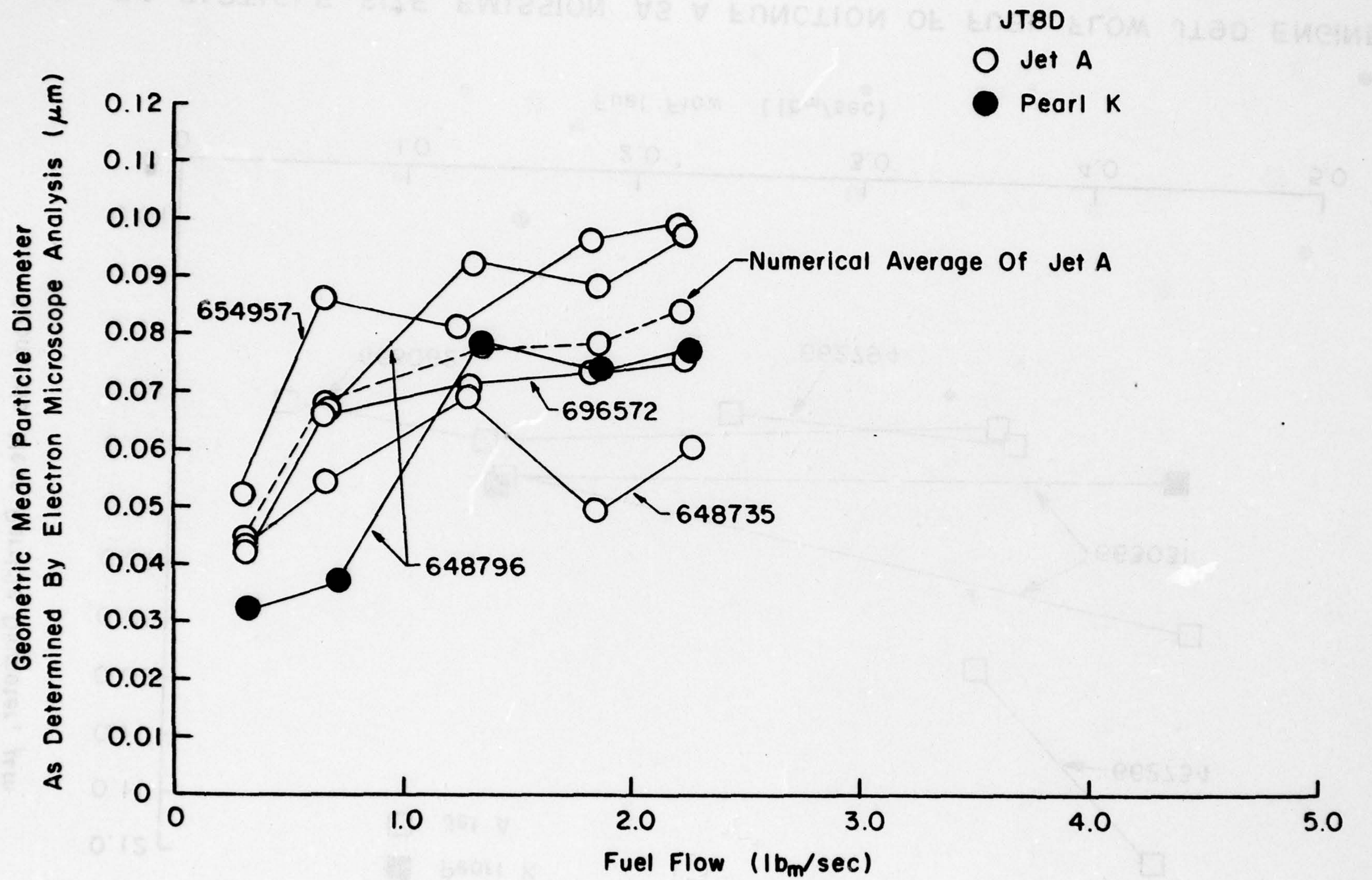


Fig. 33 PARTICLE SIZE EMISSION AS A FUNCTION OF FUEL FLOW JT8D ENGINE

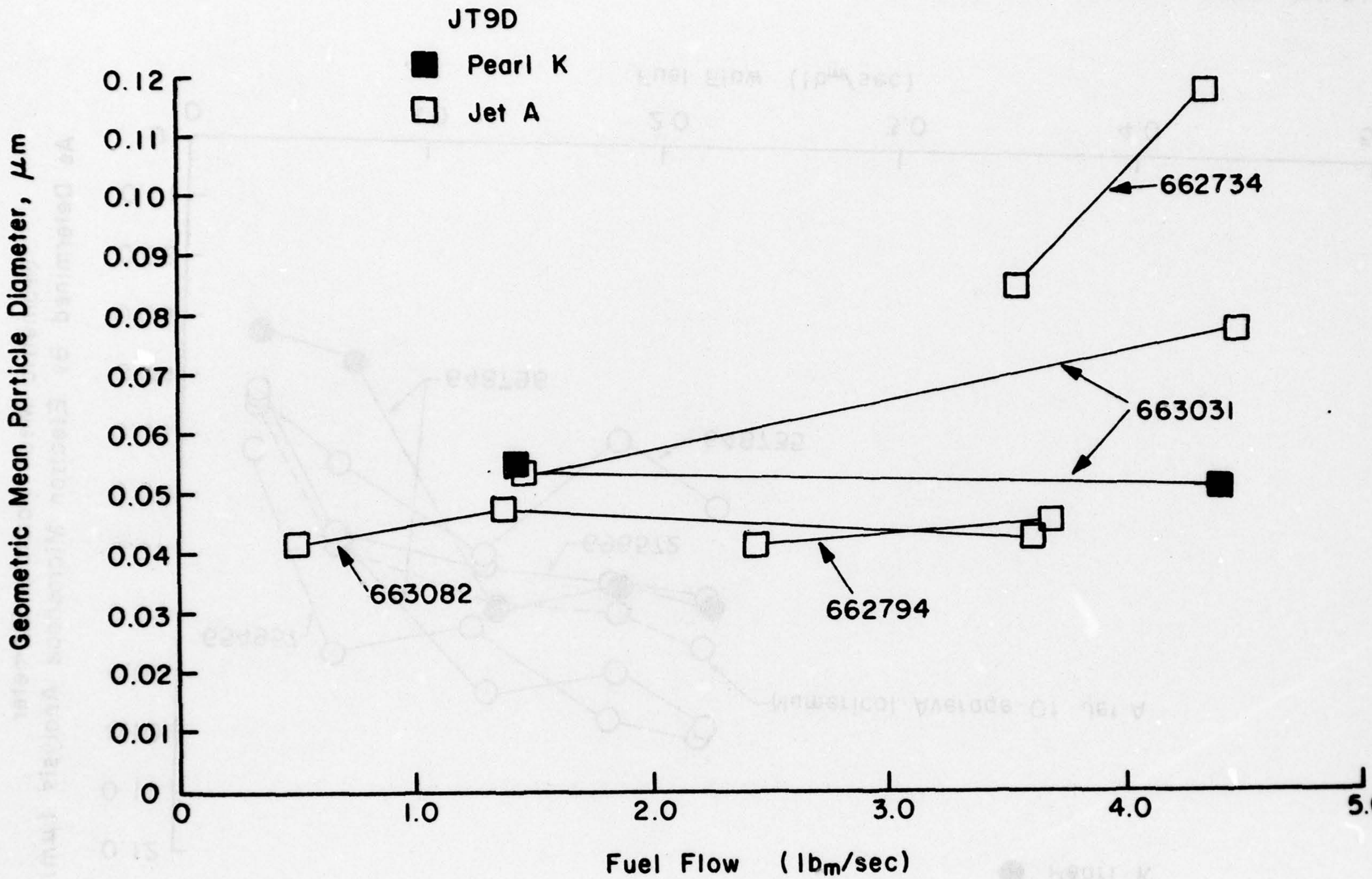


Fig. 34 PARTICLE SIZE EMISSION AS A FUNCTION OF FUEL FLOW JT9D ENGINE

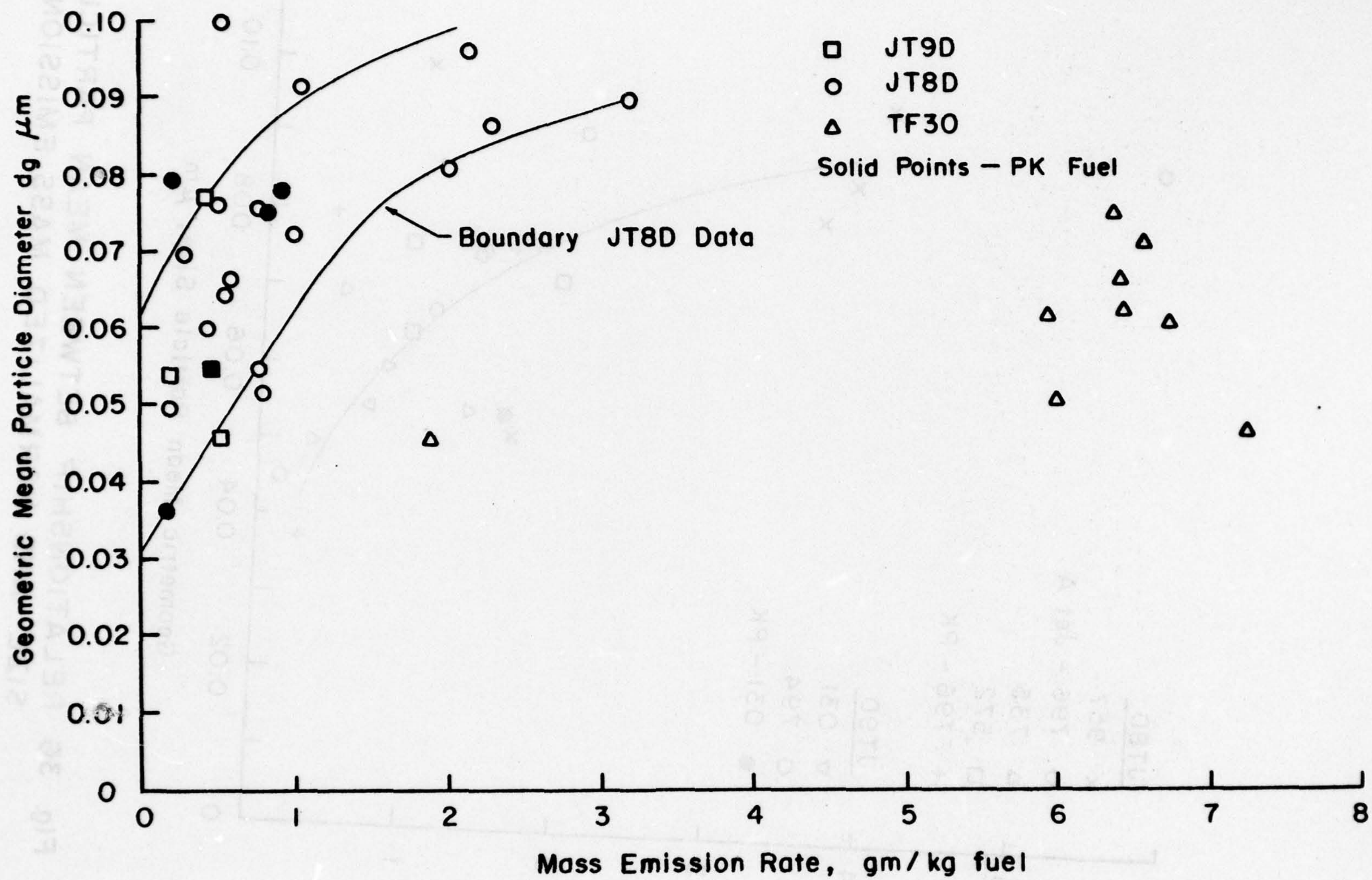


Fig. 35 RELATIONSHIP BETWEEN MEAN PARTICLE SIZE AND MASS EMISSIONS RATE

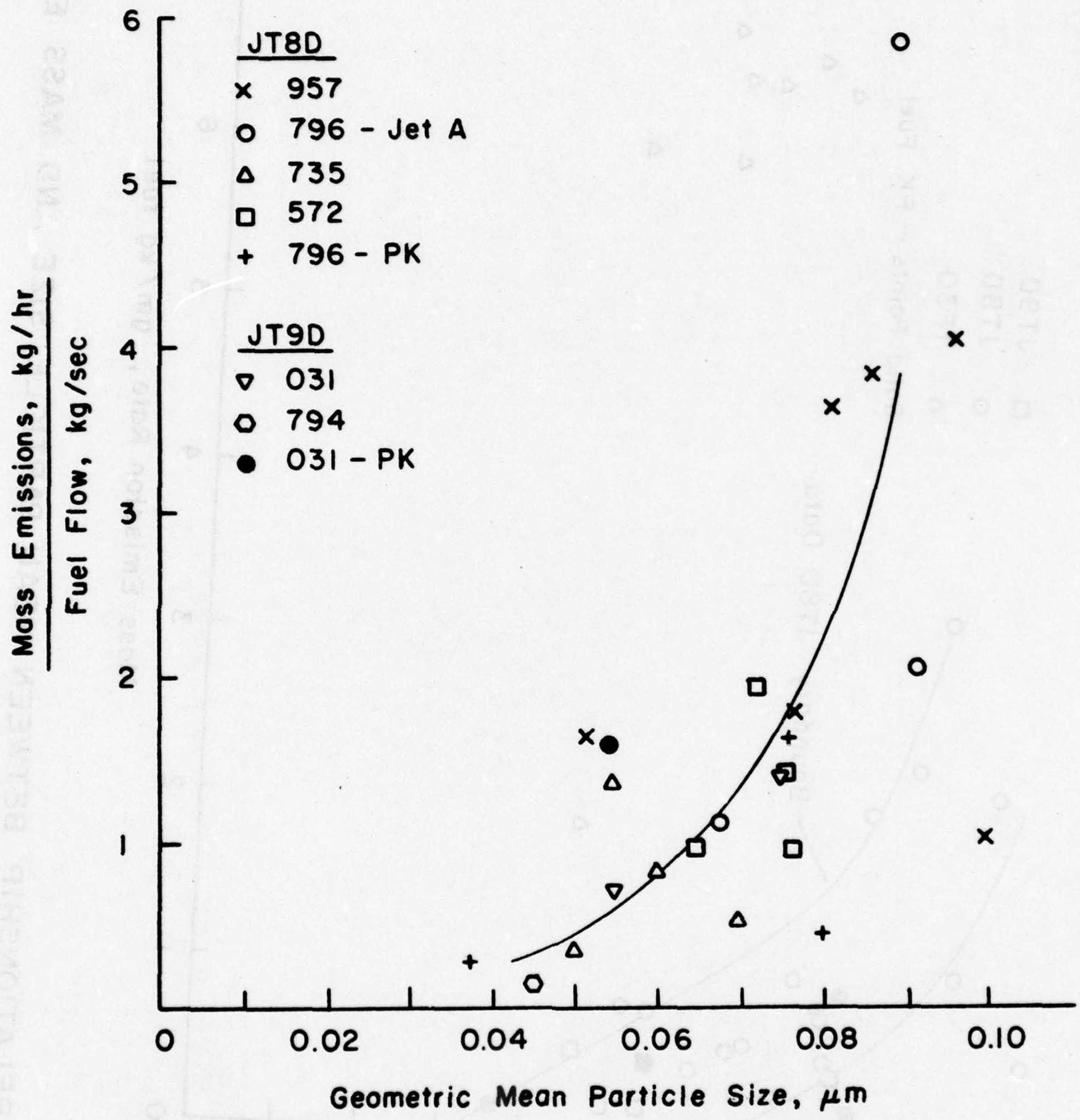


Fig. 36 RELATIONSHIP BETWEEN MEAN PARTICLE SIZE AND NORMALIZED MASS EMISSION RATE

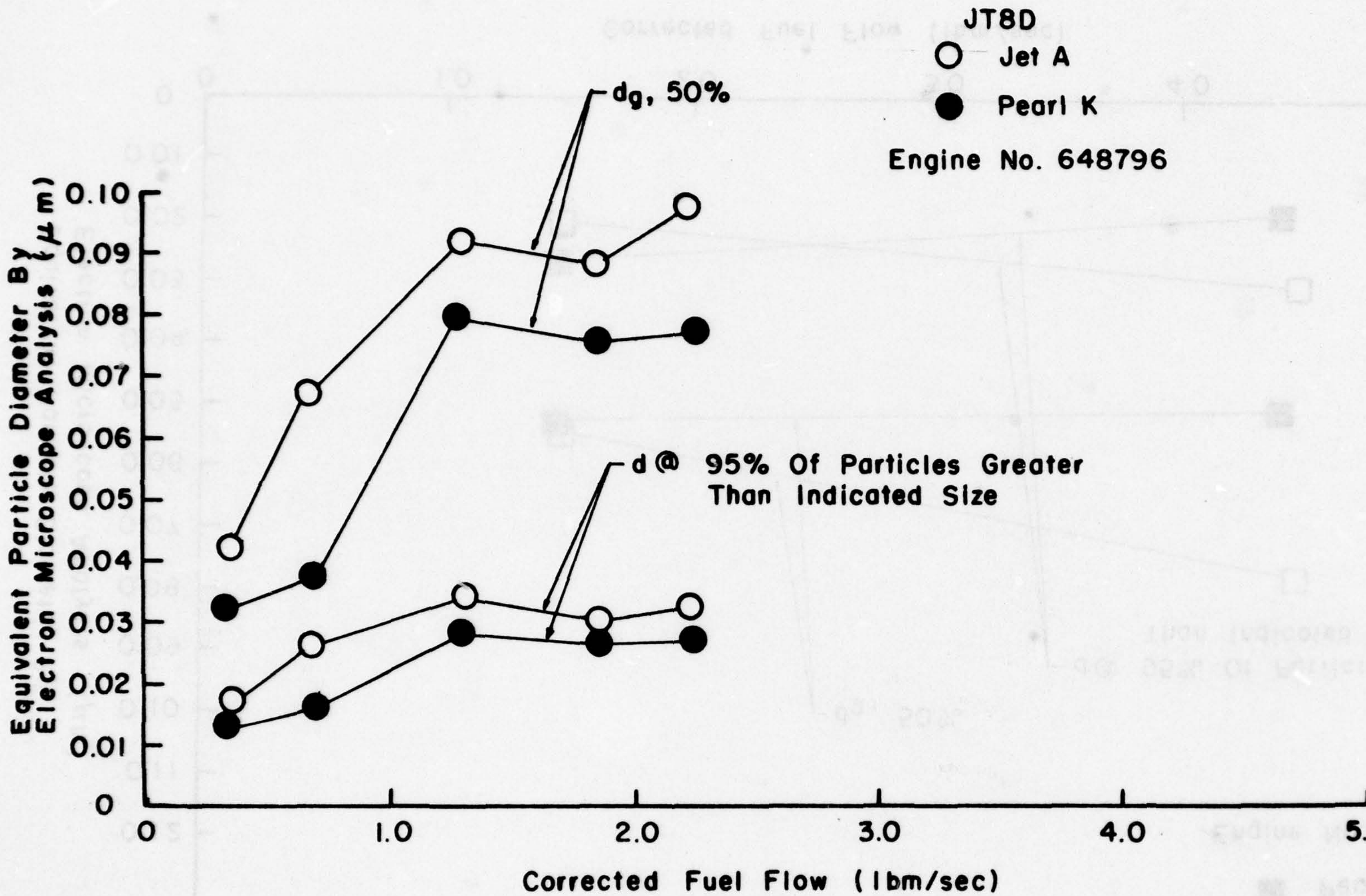


Fig. 37 EFFECT OF FUEL COMPOSITION ON PARTICLE SIZE JT8D

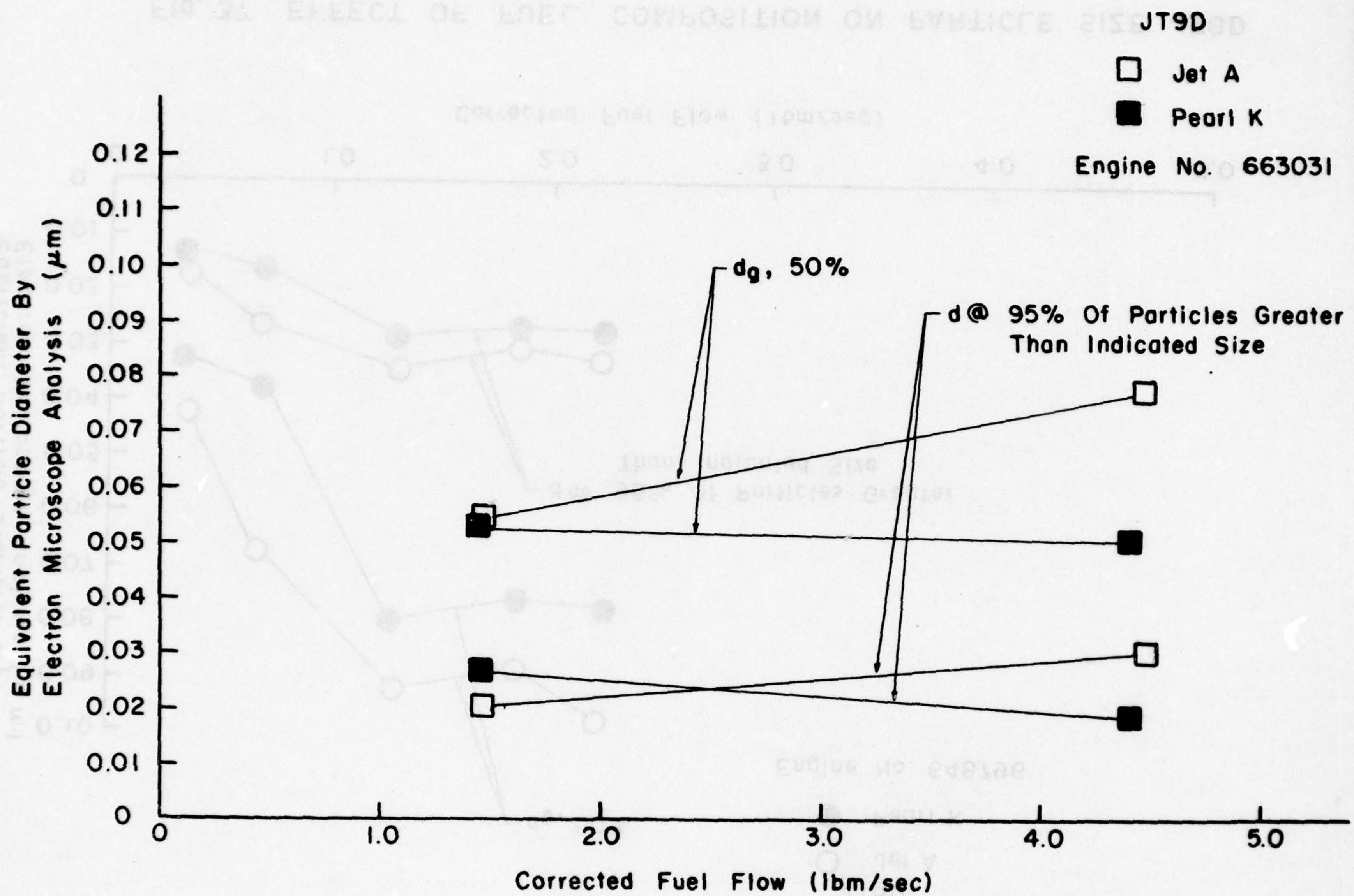


Fig. 38 EFFECTS OF FUEL COMPOSITION ON PARTICLE SIZE JT9D

aromatic content, or an increase of 0.05 percent in hydrogen content.

Comparison of the particle size data for JT8D engine 648796 on PK fuel with the average values for the four JT8D engines on Jet A fuel shows larger mean particle sizes for Jet A at idle and approach with essentially no change with increasing thrust at higher levels. The comparative values are given in Table 19. This appears consistent with the observations of Shirmer[14], who stated:

1. Smoke density is very sensitive to fuel quality at the mild turbine inlet conditions of 5 atmospheres and 1300 F. That is, smoke emission is markedly reduced as the fuel hydrogen content increases.
2. The effect of fuel quality becomes less important as the severity of the turbine inlet conditions increases.

The test conditions described by Shirmer in Note 1 above closely match the JT8D engine turbine inlet pressure and temperature at approach power.

Considering the extreme difference in burnability characteristics of these fuels as measured by the normally used parameters of smoke point and hydrogen content, little relief can be realized by looking toward control of fuel characteristics to reduce engine particulate emissions. Recent changes in the commercial fuel specifications have permitted an increase in maximum aromatic content from 20 to 25 percent coupled with a permissible reduction in smoke point from 20 to 18. Using numbers developed from the analysis of the present data, a potential exists for an increase in the particle mean geometric size of between 0.002 and 0.005 μm. The range is dependent on whether smoke point or aromatic content change is used in estimating the effect. The probable effect of fuel specification change is somewhere within this range.

Figure 39 plots all the particle size distributions for the JT8D and JT9D engines. The distributions generalize into typical distributions for idle power and for other power settings above idle (no idle samples were taken for the JT9D engine). Idle power

Table 19

COMPARISON OF MEAN PARTICLE SIZE
OF EMISSIONS FROM JET A AND PK FUELS

Power Setting	Geometric Mean Particle Size, μm: Engine 796 on PK	Engine 796 on JET A	JT8D Avg. on JET A	Percentage Increase (JET A-PK)/PK: Eng. 796	All Eng.
Idle	0.032	0.042	0.045	31	41
Approach	0.037	0.067	0.068	81	84
Cruise	0.079	0.092	0.078	16	--
Climbout	0.075	0.088	0.078	17	4
Takeoff	0.077	0.097	0.084	26	9

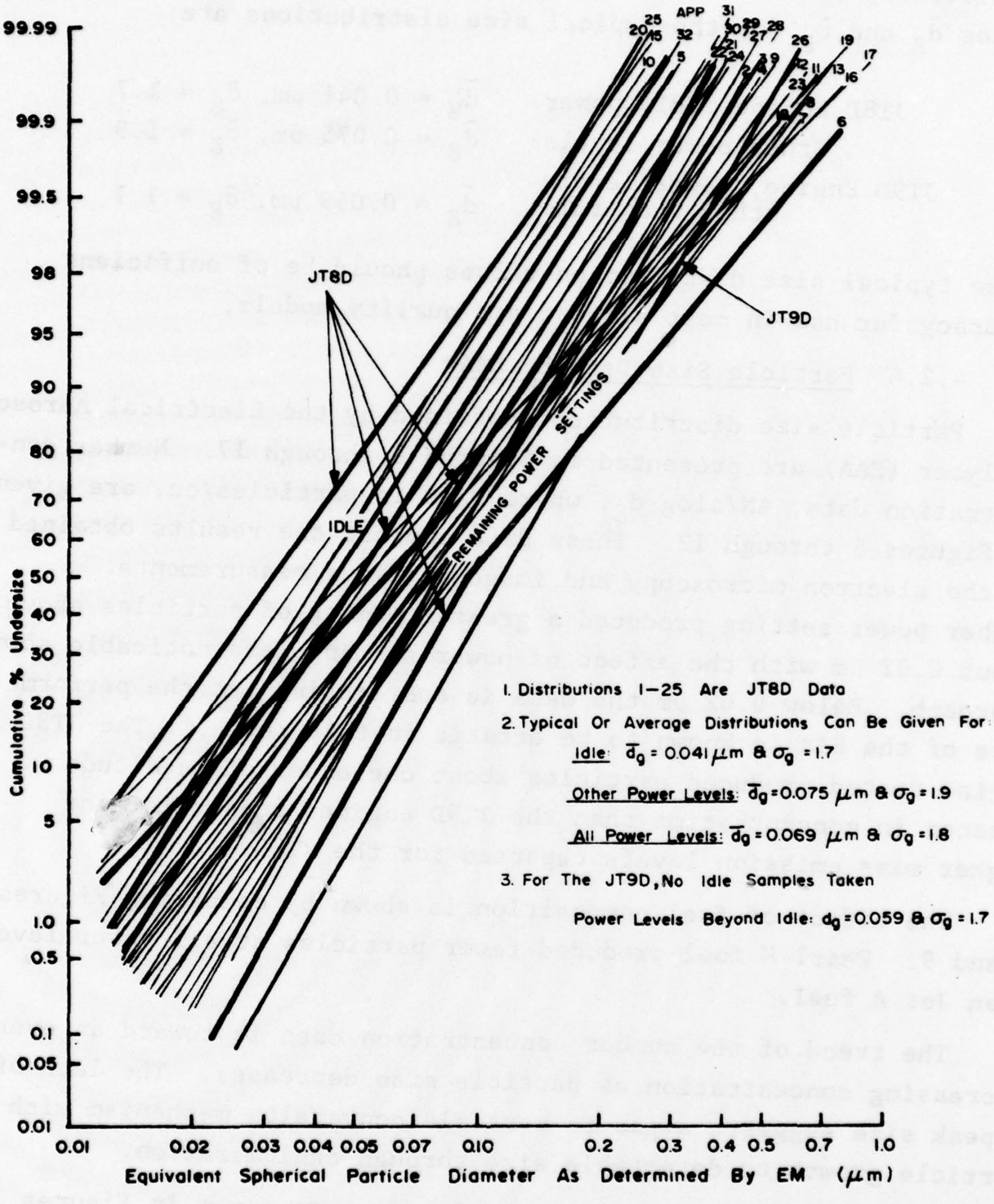


FIG. 39 LOG—NORMAL PROBABILITY PLOTS OF PARTICLE SIZE DATA

for the JT8D engine produced a distribution of particle sizes considerably smaller than those produced at higher power levels. Values $\bar{d}_g$ and $\bar{\sigma}_g$ for the typical size distributions are:

JT8D Engine, idle power:	$\bar{d}_g$ = 0.041 μm, $\bar{\sigma}_g$ = 1.7
Other power levels:	$\bar{d}_g$ = 0.075 μm, $\bar{\sigma}_g$ = 1.9
JT9D Engine, power levels other than idle:	$\bar{d}_g$ = 0.059 μm, $\bar{\sigma}_g$ = 1.7

These typical size distribution values should be of sufficient accuracy for use in most airport air quality models.

4.2.4 Particle Size Data by EAA

Particle size distributions obtained by the Electrical Aerosol Analyzer (EAA) are presented in Figures 8 through 17. Number concentration data, $\Delta N/\Delta \log d_g$, where N is in particles/cc, are given in Figures 8 through 12. These data support the results obtained by the electron microscopy and image analyzer measurements. Higher power setting produced a greater number of particles above about 0.02 μm with the effect of power setting less noticable above approach. Below 0.02 μm the data is conflicting but the performance of the EAA is known to be erratic in this range.[6] The JT8D engine tested produced particles about one order of magnitude greater in concentration than the JT9D engines supporting the higher mass emission levels reported for the JT8D.

The effect of fuel composition is shown by comparing Figures 8 and 9. Pearl K fuel produced fewer particles at all power levels than Jet A fuel.

The trend of the number concentration data is toward an ever-increasing concentration as particle size decreases. The lack of a peak size suggests a gas to particle conversion mechanism with particle growth to detectable size through agglomeration.

Volume distribution data, $\Delta V/\Delta \log d_g$, are given in Figures 13 through 17. Figures 13 and 14 show the effect of fuel composition. In general, the volume concentration is reduced with PK fuel. For

particle sizes less than about 0.1 μm, power level has little influence on the volume distribution. For larger particles power level appears to have a significant effect. The volume concentration of particles greater than 0.1 μm increases uniformly over the power levels from approach to takeoff for the test with PK fuel. With Jet A fuel and the other engines the effect of power level is not as discernible above approach power. For power settings above idle the volume distributions generally peak at 0.13 μm while the distributions at idle power peak at 0.075 μm.

4.2.5 Particle Shape

Particle shape data, Figures 18-25, are not readily quantified but the trend is for particle structure to be more complex, or agglomerated, at the higher power levels and that the larger particles are more complex than the smaller particles.

As an aid in interpreting the shape factor, A/P^2, Table 20 is presented. The shape factor for a disc, the two dimensional representation of a sphere, is $\frac{1}{4}\pi$ or 0.0795. A 5-chain agglomerate has a shape factor of 0.0159; a 10-chain, 0.0078; and a 50-chain, 0.00016. Thus, as the shape factor decreases the particles are less spherical and more highly agglomerated. Engines 696572 and 663082 illustrate best the increased complexity of particle structure with increasing size and power level. The assessment of particle structure is borne out by electron photomicrographs of the exhaust particles, Figures 40 and 41.

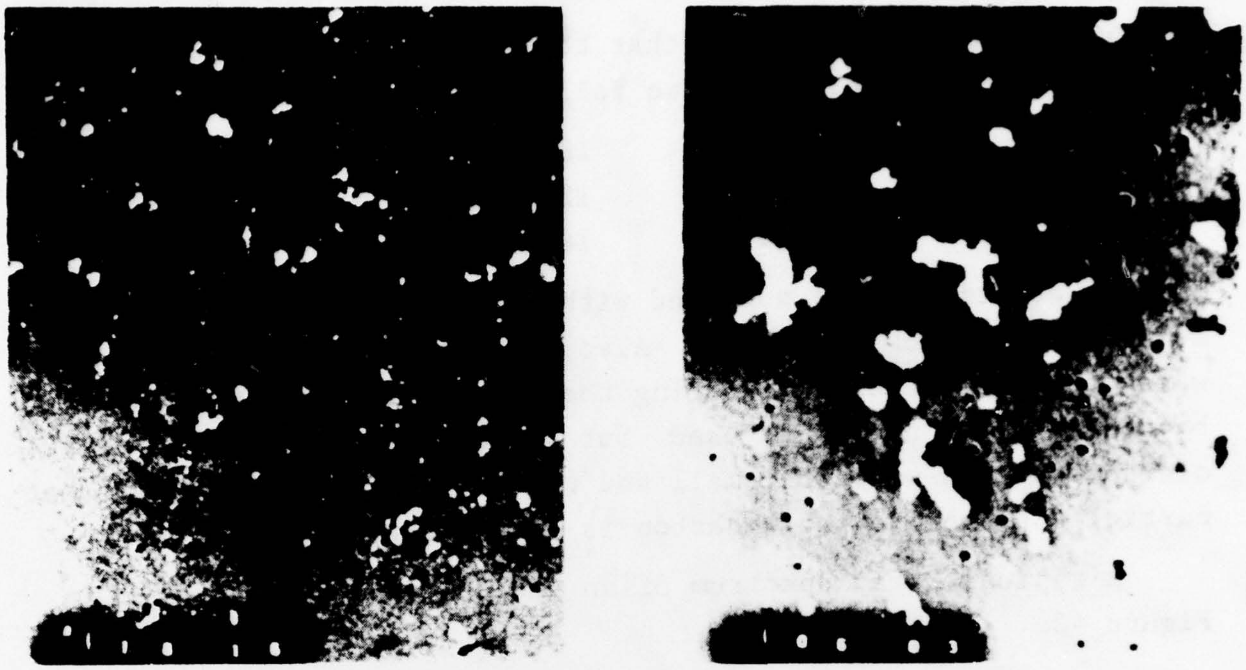
4.2.6 Elemental Analysis

The elemental analysis of the individual particles was determined by energy dispersive X-ray analysis. No spectrum was obtained indicating the composition of the particles consisted of elements below the atomic number of sodium and are essentially carbonaceous. Jet A fuel is delivered to United Airlines via pipe line. A non-metallic fatty acid, anticorrosion agent is added at the refinery along with a biocide, "Biobor", an organic borane compound. Analytical tests show that the anticorrosion agent is

Table 20

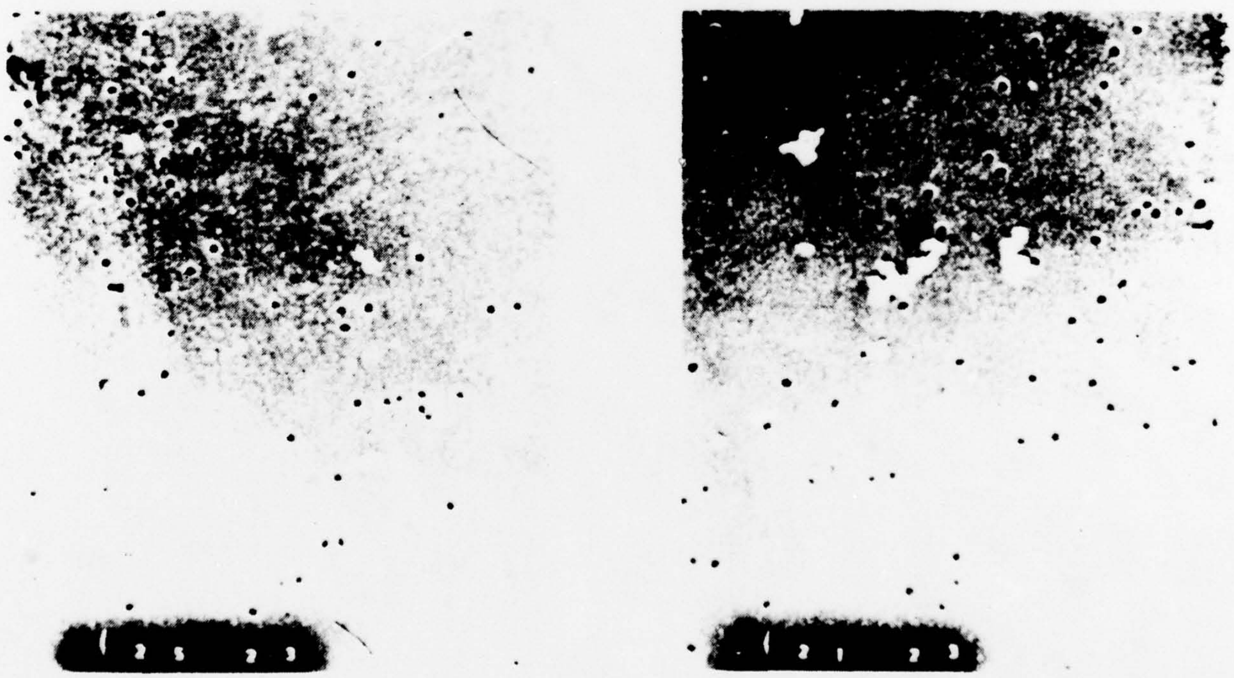
PARTICLE SHAPE CHARACTERIZATION

Number of Particles in Agglomerate Chain	Aspect Ratio l/d	P/d Ratio	Shape Factor A/P^2
1	1:1	3.14	0.0795
3	3:1	9.42	0.0265
5	5:1	15.7	0.0159
10	10:1	31.4	0.0078
50	50:1	157	0.00016



Idle Climbout

Fig. 40 - Particulate emissions, JT8D engine, JET A Fuel.



Idle Climbout

Fig. 41 - Particulate emissions, JT9D engine, JET A Fuel.

used up during transport and that the concentrations of "Biobor" during the engine tests were as follows:

January	18 - 20 ppm
April	12 - 13 ppm
June	16 - 20 ppm

No additives were supplied with the PK fuel as it was delivered by truck to United. Also, no "smoke" reducing compounds were added to either fuel during the tests. Boron is not detected by the analysis procedure used, but its contribution to the particle composition would be small and the conclusion that the exhaust particles are principally carbon is not altered.

A typical X-ray spectrum of an exhaust particle is given in Figure 42.

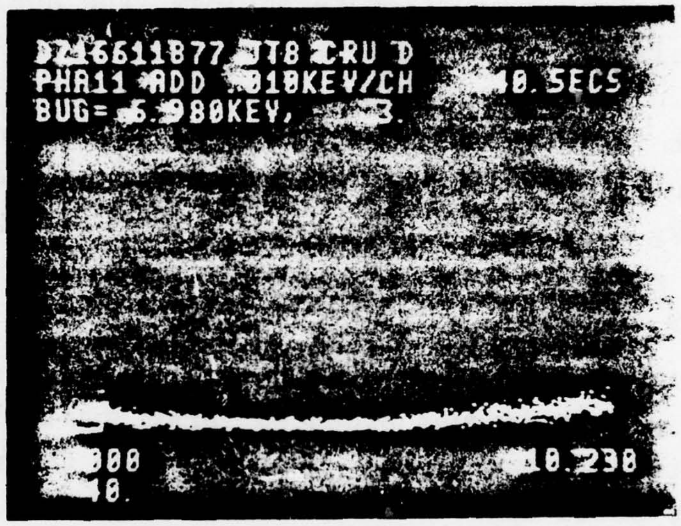


Fig. 42 - Energy dispersive x-ray spectrum of particle D emitted from a JT8D engine at cruise power.

5. CONCLUSIONS AND RECOMMENDATIONS

Resulting from this program is a particulate matter sampler for characterizing the particulate emissions from low bypass ratio, mixed flow, and high bypass ratio aircraft turbofan engines and data characterizing the emissions from the TF-30, JT8D, and JT9D engines. The particulate emissions were characterized as to their mass, particle size, particle shape, and elemental composition. The three engines tested represent different eras in power requirements, engine design, combustion technology, and application of emission controls. A summary of mass emission rates and the particle sizes of the particulate emissions is given in Table 21. The improvement in emissions with combustion technology is significant. At cruise power levels, the TF-30 produced 6.71 grams of emissions per kg of fuel consumed, the JT8D, 1.10 g/kg fuel, and the JT9D, 0.08 g/kg fuel. At takeoff the respective emissions were 6.90, 0.59, and 0.38.

Mean particle sizes correlated directly with mass emission rates. Higher power settings produced larger particles with the effect most noticable between idle and approach power and weaker at power levels above approach. Particle shape data, although lacking quantification, showed a trend toward a more highly agglomerated structure at the higher power levels and that the larger particles were more agglomerated than the small particles. The particles are esentially carbonaceous in composition.

Fuel composition influenced mass emission levels and the particle sizes to a limited extent. The engines tested on both PK and Jet A fuel generally produced lower emissions and smaller particles when using PK fuel. Pearl K fuel has a higher smoke point (35 vs $\sim$ 20 mm), a lower aromatic content (1 vs $\sim$ 20%), and a higher hydrogen content (14.25 vs $\sim$ 13.5%) than Jet A fuel. Therefore, the burnability characteristics of these two fuels are extremely different. The particle size decreases about 0.001 μm for each increase in smoke point, reduction of 1 percent in aromatic content, or an increase of 0.05 percent in hydrogen

Table 21

SUMMARY OF MASS EMISSIONS RATES AND PARTICLE SIZES OF EMISSIONS
JET A FUEL

MASS EMISSIONS

Power Setting	TF30 kg/hr Range	TF30 kg/hr Avg.	TF30 g/kg fuel Range	TF30 g/kg fuel Avg.	JT8D kg/hr Range	JT8D kg/hr Avg.	JT8D g/kg fuel Range	JT8D g/kg fuel Avg.	JT9D kg/hr Range	JT9D kg/hr Avg.	JT9D g/kg fuel Range	JT9D g/kg fuel Avg.
Idle	0.76-1.80	1.28	1.85-4.41	3.13	---	0.40	---	0.79	---	--	---	--
Approach	6.40-7.00	6.70	5.94-6.57	6.23	0.60-2.56	1.82	0.53-2.32	1.07	---	0.49	---	0.20
Cruise	13.6-15.6	14.37	6.34-7.27	6.71	0.60-4.11	2.30	0.29-2.02	1.10	---	0.33	---	0.08
Climbout	15.3-16.3	15.80	5.63-6.00	5.82	0.54-9.84	4.60	0.18-3.23	1.52	---	0.32	---	0.05
Takeoff	20.9-22.0	21.45	6.74-7.06	6.90	1.60-2.81	2.14	0.44-0.77	0.59	---	2.80	---	0.38

GEOMETRIC MEAN PARTICLE SIZE, μm

Power Setting	TF30 Range	TF30 Avg.	JT8D Range	JT8D Avg.	JT9D Range	JT9D Avg.
Idle	---	0.046	0.042-0.052	0.045	---	0.043
Approach	---	0.063	0.054-0.086	0.068	0.043-0.054	0.049
Cruise	0.063-0.075	0.066	0.069-0.092	0.079	---	0.042
Climbout	---	0.050	0.049-0.096	0.077	0.043-0.084	0.057
Takeoff	---	0.060	0.060-0.099	0.083	0.077-0.117	0.097

content, thus small changes in fuel composition will only marginally affect the particle size of the emissions. However, recent changes in commercial fuel specification to increase the aromatic content and reduce the smoke point may only increase particle size and mass emission levels.

It is recommended that additional tests be conducted to provide baseline emission data and establish variability among fleet engines. The additional tests should incorporate longer sampling times. Redesign and repackaging of the sampler is recommended to provide a more compact, mobile sampling unit. The redesign should incorporate the modifications and operational procedures developed during the engine testing phase of the programs and reworked into the present sampler.

The major conclusions from this program are listed in Table 22.

Table 22

CONCLUSIONS RESULTING FROM THE CHARACTERIZATION OF TURBINE ENGINE PARTICULATE EMISSIONS

1. Mass emission rates for a TF-30-P-1 engine using Jet A fuel increased with power setting from 1.28 kg/hr at idle to 21.45 kg/hr at takeoff. The emissions ranged from 3.13 g/kg fuel burned at idle to 6.90 g/kg of fuel burned at takeoff.

2. Mass emission rates for the JT8D engines tested on Jet A fuel increased with power settings throughout climbout from 0.40 kg/hr at idle to 4.60 kg/hr at climbout. The average emission rate at takeoff was 2.14 kg/hr. The climbout emissions were influenced by one extreme value. If this value is rejected the average climbout emission rate was 2.85 kg/hr. When based on fuel consumed, the emission rates were 0.79 g/kg at idle, 1.52 g/kg at climbout, and 0.59 g/kg at takeoff. With the extreme value rejected, the climbout value dropped to 0.95 g/kg of fuel consumed.

3. Mass emission rates for the JT9D engines tested on Jet A fuel were 0.49 kg/hr at approach and 2.8 kg/hr at takeoff. Based on fuel consumed the emissions were 0.20 g/kg and 0.38 g/kg, respectively. No idle data was taken.

4. Using Jet A fuel at cruise power, the TF-30-P-1, an engine of the pre-smoke technology era, emitted 6.71 grams of particulate matter per kg of fuel consumed compared to 1.10 g/kg for the JT8D engines and 0.08 g/kg for the JT9D engines. Thus, engine and combustion technological improvements have significantly decreased the emissions from aircraft turbine engines.

5. The particles emitted by all three engine types are generally below 0.1 μm in size. Particle sizes are dependent upon power setting. At idle, the geometric mean particle diameters, d_g, ranged from 0.042 to 0.052 μm for all three engine types listed. At takeoff the average d_g was 0.06 μm for the TF-30, 0.083 μm for the JT8D, and 0.097 μm for the JT9D. One takeoff JT9D test produced a geometric mean particle diameter of 0.117 μm. The geometric standard deviations of the particle size distributions ranged from 1.6 to 2.3.

6. Particle shape was extremely difficult to quantify. A trend toward a more highly agglomerated structure at the higher power levels was noted in some instances. The larger particles were more highly agglomerated than the smaller ones.

7. The exhaust particles are essentially carbonaceous in composition.

(Table 22 - continued)

8. Particle concentration data obtained with an Electrical Aerosol Analyzer showed the JT9D engine produced fewer particles than the JT8D. Particle concentrations ranged from about 0.3 million particles/cc to 114 million particles/cc. Results were variable with no consistent pattern discernable.

9. PK fuel, a fuel with burnability characteristics extremely different than Jet A, noticeably affected emission characteristics. Where both fuels were used on the same JT8D engine mass emission rates were lower and particle sizes smaller.

10. Results indicate a considerable variability among engines from the same series. Small sample size and budgeting and engine running time constraints contributed to the variability.

11. Additional testing is needed to provide baseline emission data and establish the variability among fleet engines. The additional tests should incorporate longer sampling times into the test plan.

12. The FAA-IITRI sampler proved its ability to acquire samples of turbine engine emissions suitable for particulate matter characterization and to function in a reliable and reproducible manner. Based on the experience obtained, redesign and repackaging of the sampler is recommended to provide a more compact, mobile sampling unit. The Electrical Aerosol Analyzer malfunctioned in the test cell environment and must be located in the control room or other location remote from the noise and vibrations of the test cell.

REFERENCES

1. Aerospace Recommended Practice, Aircraft Gas Turbine Engine Exhaust Smoke Measurement, ARP 1179, Society of Automotive Engineers, Inc. 400 Commonwealth Drive, Warrendale, Pa. 15096.

2. Nelson, A. W., "Collection and Assessment of Aircraft Emissions Baseline Data - Turbine Engines", Final Report. EPA Contract 68-02-0027, Feb. 1972.

3. Klarman, A. F., "Evaluation of a Sampling Train Procedure for Measuring Gas Turbine Engine Particulates", Final Report. NAPTC-LR-76-8, Naval Air Propulsion Test Center, New Jersey, April 30, 1976.

4. Johansen, K. M. and Kumm E. L., "Determination of Aircraft Turbine Engine Particulates", Final Report, AiResearch Manufacturing Company, Phoenix, Ariz., EPA Contract 68-02-1236, May 1975.

5. Davidson, D. L., Domal A. F., "Emissions Measurements of a J93 Turbojet Engine", Final Report No. AEDC-TR-73-132, Arnold Engineering Development Center, Arnold Air Force Station, Tenn., 1972.

6. Sem, G. J., "Design and Application of an Electrical Size Analyzer for Submicron Aerosol Particles", 21st Annual ISA Analysis Instrumentation Symposium, Instrument Society of America, Philadelphia, Pa., May 6-8, 1975.

7. Broderick, A., private communication, Department of Transportation, Boston, Mass., Oct. 10, 1975.

8. Fiorentino, A. J., Greene, W., Roberts, R., "Evaluation of Federal Aviation Administration Engine Exhaust Sampling Rake", Contract NAS3-19447, Report No. NASA CR 135 213, United Technologies Corp., Pratt & Whitney Aircraft Group, East Hartford, Conn., June 1977.

9. Ranade, M. B., "Sampling Interface for Quantitative Transport of Aerosol". Contract 68-02-0597, IIT Research Institute, Chicago, Ill., Final Report, December 1973.

10. Ranade, M. B., "Sampling Interface for Quantitative Transport of Aerosol". Contract 68-02-1295, IIT Research Institute, Chicago, Ill., July 1976.

11. Luebcke, E. H., "Turbine Engine Particulate Emissions Characterization, Operations Manual, FAA-IITRI Particulate Matter Sampler", IITRI Project C6352, Contract DOT-FA75WA-3722, DOT-FAA, Development Section C, ALG-313, 800 Independence Ave., S.W., Washington, D.C. 20591, September 1978.

REFERENCES (cont.)

12. Liu, B. Y. H., Pui, D. Y. H., "On the Performance of the Electrical Aerosol Analyzer", J. Aerosol Science, 6, 249, 1975.

13. Anon., "Collection and Assessment of Aircraft Emissions Baseline Data--Turbine Engines", Pratt & Whitney Aircraft Report PWA-4339, Feb. 1972, Figure 82.

14. Shirmer, R. M., "Effect of Fuel Composition on Particulate Emissions from Gas Turbine Engines", reprinted from "Emissions from Continuous Combustion Systems", Plenum Publishing Corporation, 227 West 17th Street, New York, N.Y. 10011.